# UPSCALING OF RAINWATER HARVESTING AND CONSERVATION TO CROPLANDS AND RANGELANDS FOR FOOD AND RENEWABLE FUEL (BIOGAS) PRODUCTION

*JJ Anderson, TAB Koatla, E Meyer, T Thubela, U Gulwa and JJ Botha*

WATER RESEARCH COMMISSION

TT 850/21

# UPSCALING OF RAINWATER HARVESTING AND CONSERVATION TO CROPLANDS AND RANGELANDS FOR FOOD AND RENEWABLE FUEL (BIOGAS) PRODUCTION

Report

to the Water Research Commission

by


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Report No. TT 850/21

**June 2021**


WATER
RESEARCH
COMMISSION

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This report is based on the WRC project no. K5/2495.

All the data generated during the project is available from:

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**ISBN 978-0-6392-0255-6**

**Published in the Republic of South Africa**

# EXECUTIVE SUMMARY


## BACKGROUND

Poverty and food insecurity are generic to many rural villages where villagers depend on rainfed agriculture and the exploitation of natural resources for household consumption and income generation. Subsistence agriculture in rural areas assists in relieving poverty and food insecurity and is an important sector for promoting economic development. As the population increases and less land becomes available for production, more marginal areas are used for agriculture. However, much of this land is located in the arid or semi-arid areas with marginal soils, and low and erratic rainfall, where much precious water is soon lost as surface runoff and evaporation. The lack of sufficient water has prevented many people from growing crops and producing livestock, resulting in severe food shortages.

Frequent droughts have highlighted the risks to human beings and livestock. While irrigation may be the most obvious response to drought, it has proved costly and can only benefit a fortunate few. Rainwater harvesting (RWH) is a low-cost alternative, where runoff water is harvested and utilised for productive purposes. Both yield and reliability of production can be improved, especially by making use of in-field rainwater harvesting (IRWH). Therefore, the application of appropriate rainwater harvesting and conservation (RWH&C) techniques in homestead gardens, croplands and rangelands in selected rural villages in South Africa could empower villagers to produce their own crops using arable land more productively and enhance livestock production, hence contributing to the reduction of household food insecurity.

Since livestock production is already an important component of many smallholder farming systems, manure can be used to produce biogas, which is a simple, cost-effective, environmentally friendly renewable energy source. Additionally, the by-products of biogas production provide organic waste of superior quality that can be used as a fertilizer. The manure-based biogas digester systems are considered ecologically friendly, since the technology captures and utilises methane directly, thereby limiting total greenhouse gas emissions from livestock. The biogas can be used for cooking, heating and lighting, and is less harmful to the environment than smoke from open wood fires. However, a sustainable water and manure supply is essential for the successful implementation and meaningful impact of biogas generation. Adequate water for the biogas digester can be collected from rooftops in tanks.

Various RWH and biogas technologies are used at sites scattered around the country. However, there is no single rural village where an integrated approach to economic development based on food, energy and water security is used. This emphasised the importance of conducting a research and development (R&D) project on RWH in homestead gardens for food and biogas production. By applying suitable RWH&C practices, especially IRWH that combines the advantages of RWH, no-till and basin tillage, villagers will be able to produce a variety of crops in their homestead gardens to provide their families with a nutritional meal throughout the year. This can be complemented by adding roof water harvesting for household consumption, supplementary irrigation and a water source for biogas production. The production of low-cost biogas as a renewable energy source will address the rising electricity costs, while the by-product can be used as an alternative source of fertilizer. Rainwater harvesting and biogas production are sustainable technologies that can improve the household's income and livelihood status, and alleviate hunger and poverty in many rural communities.

The Water Research Commission (WRC) has initiated and funded a project titled "Upscaling of rainwater harvesting and conservation to croplands and rangelands for food and renewable fuel (biogas) production". The project was conducted over a period of six years (2015–2021) in the Krwakrwa and Upper Ncera villages near the town of Alice, as well as at the Fort Cox College of Agriculture and Forestry, in the Eastern Cape.

The research team was a multidisciplinary team consisting of researchers, employees and students from the Agricultural Research Council-Soil, Climate and Water (ARC-SCW) (the lead organisation), the Eastern Cape Department of Rural Development and Agrarian Reform (DRDAR), the Fort Cox College of Agriculture and Forestry and the University of Fort Hare.

The aim of the project was to assess the upscaling of RWH&C practices on croplands and rangelands for food and renewable fuel (biogas) production that will improve rural livelihoods without impacting negatively on the environment.

**OBJECTIVES**

The project was conducted to assess the upscaling of RWH&C practices on croplands and rangelands for food and renewable energy (biogas) production. In order to achieve this aim, the specific objectives were as follows:

- Do an in-depth literature review on RWH&C to improve production on homestead gardens, rangelands and croplands through functional institutional arrangements, as well as the application of biogas as a renewable energy source in semi-arid areas.
- Describe the natural and human resources, institutional arrangements, and organisational structures and farming systems in the study area.
- Demonstrate and evaluate appropriate RWH&C techniques for increased crop and livestock production on homestead gardens, croplands and rangelands, with particular attention to biogas from cattle manure as a source of renewable energy at a household and/or village scale for a combination of food and fuel production systems.
- Investigate, understand and implement workable institutional arrangements through the rediscovery of previous functional and dysfunctional working rules for increased crop and livestock water productivity (LWP) for a combination of food and fuel production systems.
- Evaluate the social acceptability, and financial and economic feasibility of biogas generation to meet energy demands at household and/or village scale within appropriate institutional arrangements and organisational structures.
- Investigate best management practices of livestock (cattle) for manure collection and transportation to biogas digesters as a renewable energy source.
- Evaluate the suitability, effectiveness and possible practical application of biogas effluent as a liquid fertilizer.
- Assess, monitor and evaluate the quantity of harvested roof water and its use within the homestead for biogas production, crop production and domestic use.
- Evaluate rangeland rainfall use efficiency (RUE), water use efficiency (WUE) and water use productivity (WUP), and the use of these parameters in determining rangeland water dynamics.
- Assess the communal livestock grazing patterns, production performance and LWP over different seasons and vegetation types.

**SITE SELECTION**

Since the project focused on semi-arid areas where both rangeland and cropland farming are the most common practices, a number of rural villages in the Eastern Cape were identified for project implementation. Site-specific visits and discussions with relevant stakeholders, extension officers and village leaders were utilised for selection purposes. Semi-structured interviews were conducted with villagers to obtain more information regarding their access to energy sources, their demographics, natural resources and production in their homestead gardens, croplands and rangelands. From the results of the field observations, it was decided to implement the project in Krwakrwa Village in the Amathole District of the Eastern Cape. The neighbouring village, Upper Ncera, showed a keen interest in the project conducted in Krwakrwa Village, so it was decided to expand the project to Upper Ncera at a later stage.

## MATERIAL AND METHODS

In order to evaluate the social acceptability, and financial and economic feasibility of biogas production as a renewable energy source, and bio-slurry as a fertilizer source, on-farm and on-station demonstrations and experiments were conducted. Demonstration plots were implemented in selected homestead gardens where a variety of vegetable crops was produced, making use of the IRWH technique. This was done at the same homestead gardens where roof water harvesting was used, and bio-digesters were constructed. Limited information is available on the application method and application rate of bio-slurry as a fertilizer source. On-station experiments were therefore conducted at Fort Cox College to investigate this. Institutional arrangements need to be in place to ensure that optimal use is made of the biogas and RWH&C technologies. For that reason, past and current institutional arrangements were investigated, and new and improved ones implemented to improve production in the croplands and rangelands.

## INSTITUTIONAL ARRANGEMENTS

The two villages were faced with many challenges that hindered the effective utilisation of homestead gardens, crops and rangelands for crop and livestock production. One of these challenges was the poor implementation or lack of institutional arrangements. Formal and informal meetings and discussions were held with villagers to find out how the institutions and institutional arrangements within the village have helped improve or suppress agricultural production. Information was gathered by making use of a structured questionnaire and one-on-one interviews.

Initially, villagers found it difficult to understand the concept of institutions and institutional arrangements, but once they understood it as specific rules and regulations within the village, they were able to identify old, existing and new rules that could promote the productive use of crops and rangelands. Most of the rules were dysfunctional and there was a problem with their implementation and enforcement. The adherence of the institutional arrangements was challenging, since some people no longer acknowledge the authority of the traditional leadership due to too much political interference in the villages. After extensive engagement with all the affected parties, including the traditional leadership, smallholder farmers, villagers, the municipality and other relevant stakeholders, it was agreed that institutional arrangements are critical for the development of the villages. Committees were formed to assist in implementing, monitoring and evaluation (M&E) and giving fines to those who failed to adhere to the institutional arrangements. This paved the way for the implementation of the project.

## ROOF WATER HARVESTING

Water collected from rooftops and stored in tanks was used in the mixture for biogas production, supplemental irrigation for crop production in the homestead gardens and for domestic purposes. Not only was it necessary to investigate whether enough rainwater could be harvested to feed the bio-digesters on a daily basis with a mixture of cattle manure and water, but also to know if the quality of the collected water is suitable for biogas production, supplemental irrigation and domestic use. Analyses of collected water samples revealed that the water collected from rooftops was suitable for domestic and irrigation use. However, no microbiological or heavy metal analyses were done that could have a negative effect on the safe use of the water.

## HOMESTEAD CROP PRODUCTION

Various RWH&C practices were identified from the available literature for implementation in homestead gardens, but the IRWH technique was found to be the most sustainable technique for implementation in homestead gardens and croplands under the current agro-ecological conditions in the Krwakrwa and Upper Ncera villages.

Villagers were equipped with the necessary knowledge and skills to implement and use the IRWH techniques for food production in the homestead gardens. Initially, the adoption rate of the IRWH technology was low, but as villagers realised the advantages of using this technology, it spread rapidly. With IRWH, runoff water is collected and stored in basins, allowing villagers to produce a variety of vegetable crops throughout the year. Production was further increased through the use of bio-slurry as a liquid organic fertilizer.

**CROPLAND PRODUCTION**

Villagers need to expand their production to the unutilised croplands in order to eradicate hunger and poverty in their villages. From previous research, it is already known that specially designed implements can be used to construct IRWH structures on a larger scale in communal croplands for maize production as staple food. However, IRWH, used in combination with sound soil management practices (e.g. mulching and cover crops) and bio-slurry application, can be used successfully to improve production even further. The suitability, efficiency and application of bio-slurry as an organic fertilizer for crop production has still not been evaluated under local conditions. Therefore, a decision was taken to conduct experiments under controlled conditions at Fort Cox College, where the application method and application rate of bio-slurry was investigated. A statistically laid out field experiment with 20 treatments and four replications was implemented on the Fort Cox/Valsrivier ecotope. IRWH basins were constructed and bio-slurry was applied at different application rates (0.3, 5 and 7 t $ha^{-1}$). Maize was planted as an indicator crop. Various soil and plant parameters (biomass and grain yield) were recorded to evaluate the various treatments.

Research results have shown that soil management practices have a larger impact on maize grain yield than bio-slurry application rates. When looking, for example, at the 5 t $ha^{-1}$ application, a yield trend of mulch (1,697 kg $ha^{-1}$) > cover crop (1,579 kg $ha^{-1}$) > bare: incorporate (1,485 kg $ha^{-1}$) > bare: surface application (1,448 kg $ha^{-1}$) > bare: spread application (1,352 kg $ha^{-1}$) > bare: water equivalent (1,256 kg $ha^{-1}$) > manure (1,165 kg $ha^{-1}$) was observed. Crop yield increased with higher bio-slurry application rates and performed the best where bio-slurry was incorporated into the soil before or with planting. This was because nutrients in the bio-slurry are readily available for uptake by the crop roots. The bio-slurry improved the soil structure and water-holding capacity, but the moisture in the bio-slurry was insufficient to increase plant available water (PAW) enough to have a significant impact on maize biomass and grain yield. The practicality of applying bio-slurry in the croplands in a rural village is questionable, since the small yield increase does not justify the effort to get the bio-slurry from the homestead to the cropland. The cutting of maize stalks after harvest and using it as a mulch in the basins of the IRWH crop production system is a more practical and viable option.

**RANGELAND PRODUCTION**

There is no proper veld management system in place in most rural areas. Overgrazing is common and rangelands are in a poor condition. Some croplands have not been utilised for more than 20 years and are threatened by bush encroachment. An attempt was therefore made to improve the productivity on old (arable) croplands and rangelands, so that good-quality cattle manure could become available to feed the bio-digesters. Since RWH&C techniques for use in rangelands are limited, the improvement of rangeland condition and production focused on sound veld management practices. That indirectly minimises unproductive water loss and improves the conservation of water in the soil profile. It helped to improve the vegetative cover, species composition, rangeland WUE and rangeland water productivity.

In the old lands, an experiment was conducted that was aimed at intercropping four forage legume species with one grass species, as well as implementing mechanised IRWH basins to determine their effect on forage biomass productivity. Results showed that grass-legume intercropping had no significant effect on forage dry matter yield production.

It was also observed that the grass-legume mixture plots produced a greater yield in comparison to the grass-only (control) plots, although the difference was not significant. The production from the grass-only plot was 16.05 t $ha^{-1}$, whereas the pasture production from the *Lepedeza cuneate*, *Trifolium repens* and *Lespedeza cornuculatus*, and grass mixtures was 16.93, 18.47 and 18.60 t $ha^{-1}$, respectively. Implementation of RWH&C techniques in the form of mechanised IRWH basins did not significantly affect total dry matter (TDM) yield production. Production on the control plot was 19.49 t $ha^{-1}$, while the production on the plots where mechanised basins were implemented was slightly lower (17.89 t $ha^{-1}$).

In the rangelands (natural veld), enclosure camps (2 m x 2 m) were installed at various positions in the communal grazing area. Production and species composition inside and outside the enclosure camps were recorded. Production inside the enclosure camps was higher during the summer and autumn period due to restricted grazing. During the summer period, when most production occurred, the production inside the enclosure camps was 11.92 kg $m^{-2}$, while it was only 9.44 kg $m^{-2}$ outside. Rotational grazing, where camps are allowed to rest, will thus be beneficial for improved production.

**ANIMAL MOVEMENT**

Livestock production is the main agricultural practice in many rural villages, and cattle manure can be used to produce biogas. Since a frequent supply of cattle manure is needed to feed the digesters regularly, the management of livestock movement was studied. Livestock movement was recorded by fitting GPS devices to collars that were fitted around the necks of selected animals in the Krwakrwa and Upper Ncera villages. Movement was recorded during a wet (summer) and dry (winter) period. Kraaling of animals at night was promoted to ease the collection of cattle manure in close proximity of the bio-digester.

Analysis of the livestock grazing distribution on the landscape revealed that the animals in the Krwakrwa and Upper Ncera villages spend most of their time grazing around the homesteads, along streams and near watering points in both the wet and the dry seasons. Species grazed had moderate grazing value, which is also a strong motivation for continuous grazing in these areas. An abundance of species such as *Eragrostis capensis*, *Sporobolus africanus* and *Themeda triandra* occurred in the grazing lands neighbouring homesteads, which animals preferred to other grasses in the open areas far from the homestead.

**BIOGAS PRODUCTION**

Biogas was shown to be a cost-effective, environmentally friendly energy source, as an alternative to electricity or firewood, which can be used for cooking, heating and lighting. Results from data collected at the University of Fort Hare test site have shown that biogas digesters are financially sound investments and economically feasible at both household and societal levels. Furthermore, the biogas met the energy demands at household and/or village scale within the appropriate institutional arrangements and organisational structures. Digesters were more than capable of supplying the energy required for cooking, provided that they are continuously fed at least every five days. From the gas profiles, it was possible to determine the potential avoided electrical energy costs. The financial cost of approximately R17,000 for the digester worked out to a net present value of R22,000 with a payback period of 22 months.

**RECOMMENDATIONS**

In order to ensure the continued success of the project and widespread adoption of the RWH&C and biogas technologies, the most important recommendations were the following:

- Adhere to enforceable workable and functional institutional arrangements.
- Apply roof water harvesting to ensure that water is readily available at all times.
- Empower community members with the necessary knowledge and skills to effectively implement and use RWH&C systems for household food production.

- Use effluent from bio-digesters as a fertilizer source in homestead gardens and croplands.
- Promote an effective extension service that can provide guidance and training on all aspects of crop production.
- Fence all croplands and rangelands. This will prevent roaming animals from destroying crops and RWH&C structures in the croplands and allow the implementation of a rotational grazing system in the rangelands.
- Limit livestock numbers according to the grazing capacity of the old arable lands and rangelands.
- Promote the sharing of bio-digesters to make it a more economically viable and feasible renewable energy source.
- Incentivise or partially subsidise biogas production on a household scale.

# ACKNOWLEDGEMENTS

The contributions of the following organisations and people are gratefully acknowledged:

- The Water Research Commission for initiating and funding of the project.

- The Reference Group members for their valuable inputs and support throughout the duration of the project

| | |
|---|---|
| Prof S Mpandeli | Water Research Commission |
| Dr SD Hlophe-Ginindza | Water Research Commission |
| Mr. L Nhamo | Water Research Commission |
| Dr T Everson | University of KwaZulu-Natal |
| Dr C Madakadze | University of Pretoria |
| Prof D Tinarwo | University of Venda |

- The Eastern Cape Department of Rural Development and Agrarian Reform for its support and help.

- The University of Fort Hare and its Institute of Technology for their involvement and participation.

- The Agricultural Research Council, especially the management, researchers, research assistants and administration of ARC-SCW for their support.

- The Krwakrwa and Upper Ncera Village Committee members for the assistance.

- The traditional leadership of the two villages, especially their leader, Chief Mabandla, for allowing the project team to work within their constituency and for providing much-needed support.

- The villagers from the Krwakrwa and Upper Ncera villages for applying the technologies in their homestead gardens, recordkeeping and providing information for questionnaires.

- Dr Lesoli for overseeing the rangeland project activities before his untimely passing in 2017.

- Dr Moyo for his valuable guidance on the research conducted in the arable lands and rangelands.

- Ms Kana-Venn for providing villagers with advice and support in terms of extension service, conducting village meetings and overseeing project activities in the villages.

- Mr Wessels, Mr Moshounyane, Mr Mandries, Mr Khamkham and Mr Ngqeleni for assisting with fieldwork and data capturing.

- Ms Cochrane for conducting the statistical analysis for data collected at the Fort Cox experimental plots.

- Dr Nell for the interpretation of the water analysis results.

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| | |
|---|---|
| AD | Anaerobic digestion |
| AI | Aridity Index |
| AIDS | Acquired Immunodeficiency Syndrome |
| AOB | Ammonium-oxidising bacteria |
| ARC | Agricultural Research Council |
| ARC-SCW | Agricultural Research Council-Soil, Climate and Water |
| AU | Animal unit |
| Av | Avalon |
| B | Boron |
| BD | Bulk density |
| Bv | Bainsvlei |
| C | Carbon |
| Ca | Calcium |
| CBO | Community-based organisation |
| C:N | Carbon:nitrogen ratio |
| $CH_4$ | Methane |
| Cl | Chlorine |
| $CO_2$ | Carbon dioxide |
| COD | Chemical oxygen demand |
| Cv | Clovelly |
| Cu | Copper |
| DM | Dry matter |
| DRDAR | Department of Rural Development and Agrarian Reform |
| DUL | Drained upper limit of plant available water |
| EC | Eastern Cape |
| Es | Evaporation from the soil surface |
| ET | Evapotranspiration |
| ETo | Potential evaporation |

| | |
|---|---|
| Ev | Evaporation from the crop |
| FAO | Food and Agriculture Organisation |
| Gc | Glencoe |
| GC | Grazing capacity |
| GDP | Gross Domestic Product |
| Gf | Griffen |
| Gs | Glenrosa |
| HI | Harvest Index |
| HIV | Human Immunodeficiency Virus |
| Hu | Hutton |
| IRP | Integrated Resource Plan |
| IRWH | In-field rainwater harvesting |
| K | Potassium |
| LFA | Landscape functional analysis |
| LL | Lower limit of plant available water |
| LSD | Least significant difference |
| LWP | Livestock water productivity |
| M&E | Monitoring and evaluation |
| MBC | Minimum bactericidal concentration |
| Mg | Magnesium |
| Mn | Manganese |
| MoU | Memorandum of Understanding |
| N | Nitrogen |
| Na | Sodium |
| NDP | National Development Plan |
| NGO | Non-governmental organisation |
| $NH_3$ | Ammonia |
| $NH_4$ | Ammonium |
| N-NH | Ammonia Nitrogen |

| | |
|---|---|
| $NO_3$ | Nitrate |
| NPV | Net present value |
| NUE | Nitrogen use efficiency |
| NWM | Neutron water meter |
| $O_2$ | Oxygen |
| OC | Organic carbon |
| P | Phosphorus |
| PAW | Plant available water |
| $PAW_P$ | Plant available water at planting |
| $PAW_{PM}$ | Plant available water at physiological maturity |
| $PAW_T$ | Plant available water at tasselling |
| $PO_4^{3}$ | Phosphate |
| PUE | Precipitation use efficiency |
| PV | Photovoltaic |
| R&D | Research and development |
| RCBD | Randomised complete block design |
| RDP | Reconstruction and Development Programme |
| ROI | Return on investment |
| RUE | Rainfall use efficiency |
| RWH | Rainwater harvesting |
| RWH&C | Rainwater harvesting and conservation |
| RWP | Rainwater productivity |
| Sd | Shortland |
| Se | Sepane |
| $SO_4^{2-}$ | Sulphate |
| SSSSA | Soil Science Society of South Africa |
| Stats SA | Statistics South Africa |
| SWC | Soil water content |
| SWOT | Strengths, weaknesses, opportunities and threats |

| | |
|---|---|
| TBVC | Transkei, Bophuthatswana, Venda and Ciskei |
| TDM | Total dry matter |
| TESW | Total extractable soil water |
| T-LoCoH | Time Local Convex Hull |
| TS | Total solids |
| VCS | Veld condition score |
| VFA | Volatile fatty acids |
| Vp | Vegetative period |
| VS | Volatile solids |
| We | Westleigh |
| WHO | World Health Organisation |
| WRC | Water Research Commission |
| WUE | Water use efficiency |
| WUP | Water use productivity |
| Yb | Biomass yield |
| Yg | Grain yield |
| $\theta m$ | Gravimetric soil water contents |
| $\theta v$ | Volumetric soil water contents |

# CHAPTER 1: INTRODUCTION

## 1.1 BACKGROUND

Poverty and food insecurity are generic to the rural communities of poor countries in the sub-Saharan African region. People in these areas usually depend on rainfed agriculture and the exploitation of natural resources for household consumption and income generation. Most of these areas lack industries to provide alternative employment opportunities and are often marginal for crop production due to low and unreliable rainfall, high evaporation rates and poor soil. Estimates indicate that some 840 million people worldwide were undernourished in 1998–2000. The highest percentage of these were in Africa. About 200 million people (28% of the population) in Africa suffered from malnutrition in 2003, 38 million experienced acute food insecurity, and 24,000 died every day from starvation (Clover, 2003).

As the population increases and less land becomes available, more and more marginal areas are being used for agriculture. However, much of this land is located in the arid or semi-arid areas where rainfall is low and erratic, and where much precious water is soon lost as surface runoff and evaporation from the soil surface (Es). Recent droughts have highlighted the risks to human beings and livestock, which occur when rainfall is very low, resulting in a shortage of water. While irrigation may be the most obvious response to drought, it has proved costly and can only benefit a fortunate few. There is now increasing interest in a low-cost alternative, generally referred to as “rainwater harvesting”. Rainwater harvesting is the collection of runoff for productive purposes. Instead of runoff being left to cause erosion, it is harvested and utilised. In the semi-arid, drought-prone areas where it is already practised, water harvesting is a directly productive form of soil and water conservation. Both yields and reliability of production can be significantly improved with this method. Rainwater harvesting can be considered a rudimentary form of irrigation. The difference is that, with RWH, the farmer has no control over the timing. Runoff can only be harvested when it rains. In regions where crops are entirely rainfed, a reduction of 50% in the seasonal rainfall, for example, may result in a total crop failure. If, however, the available rain can be concentrated on a smaller area, reasonable yields will still be received. However, in a year of severe drought, there may be no runoff to collect, but an efficient water harvesting system will improve plant growth in the majority of the years. Therefore, the application of appropriate RWH&C techniques on homestead gardens, croplands and rangelands in selected rural villages in South Africa could empower villagers to produce their own crops using the arable land more productively and enhance livestock production using rangelands, hence contributing to the reduction of household food insecurity.

Many rural communities are still not connected to the electricity grid or community members cannot afford to buy electricity due to the high unemployment rate. Many rural households therefore still depend on firewood to meet their energy demands for heating and cooking. The uncontrolled chopping down of trees for firewood to prepare food results in deforestation and contributes to global warming. Using fossil fuels, such as coal, also contributes to greenhouse gas emission. Smoke from open fires not only causes chronic lower respiratory infections among children under five years of age and eye problems, but also poses a fire hazard. Biogas, as a renewable energy source produced from cattle manure, can be used as a replacement for firewood for cooking. Biogas production leads to less air pollution and mitigates greenhouse gas emissions. Furthermore, the by-product of the biogas digesters provides organic waste of superior quality that can be used as an organic fertilizer.

Work conducted by Everson et al. (2015) has shown that digested animal manure (bio-slurry) can be used as an organic mulch since it contains bulk and fibre, which holds soil moisture. Their research further revealed that the bio-slurry also forms a hard cap of organic material, which has the potential to reduce soil evaporation. However, limited information is available on the use of bio-slurry as a fertilizer source in a rural setting. More information on the method of application and application rate is therefore needed to promote it as a management option for food production in rural communities.

## 1.2 MOTIVATION

The capture of rainfall at or near the place where it falls is an obvious solution to the problem of water access, and is one that has been practised for thousands of years. Some advantages of rainwater harvesting for domestic and agricultural water supply are clear:

- Water on the spot, where the household or crops and/or plants or animals need it
- Water under the control of the individual household, as opposed to a communally managed system
- In all but the driest of climates, the possibility of capturing significant quantities of water

However, there are drawbacks too. Roof water harvesting for domestic water supply is expensive; the greater part of the cost is the storage facility needed to carry the users through dry periods. Long dry seasons pose obvious difficulties for RWH and it may not be able to provide a year-round supply of water.

In the rural areas, large portions of rangeland veld are used as agricultural land. These areas are owned and managed communally by traditional leaderships. Rangelands are used primarily for grazing domestic livestock, and secondarily for harvesting natural products such as medicinal plants, firewood and other resources. These areas are often in a poor state due to overgrazing associated with mismanagement. Loss of grass cover through overgrazing on rangelands has resulted in poor water infiltration, high evaporation from the soil surface, increased runoff and severe soil erosion. Rehabilitation of the degraded rangelands by making use of appropriate management practices and RWH&C techniques can improve the carrying capacity of the natural veld, which will result in improved animal production. However, in communal areas, crop and livestock farmers often share the same production area. It is thus not uncommon for livestock to be allowed to graze in the croplands after the crop has been harvested, where maize stalks are used as fodder for the animals. Nevertheless, where RWH structures have been implemented in the croplands, grazing by livestock should be practised in a controlled manner, minimising the potential conflict situations between crop and livestock farmers, which results from the destruction of crops and RWH structures by animals. It is therefore important for rules and regulations (institutions and institutional arrangements) to be in place to ensure the smooth running of various farming operations in the rural villages. The success of the village-based management of resources will thus depend on the functioning of institutional arrangements.

Since livestock production is already an important component of many smallholder farming systems, livestock manure can be used to produce biogas, which is a cost-effective, environmentally friendly energy source. Biogas is an alternative source of energy to firewood that will decrease environmental degradation and erosion resulting from deforestation. Biogas provides a renewable and environmentally friendly process that supports sustainable and integrated agriculture. It is one of the simplest sources of renewable energy and can be derived from sewage, liquid manure from chicken, cattle and pigs, and/organic waste from agriculture or food processing. Additionally, the by-products of the digesters provide organic waste of superior quality that can be used as fertilizer. The manure-based biogas digester systems are considered ecologically friendly since the technology captures and utilises methane directly, thereby limiting total greenhouse gas emissions from livestock. The biogas can be used for cooking, heating and lighting, and is less harmful to the environment than smoke from open wood fires. It causes less air pollution and is safer to use. However, a sustainable water and manure supply is essential for the successful implementation and meaningful impact of biogas generation. Adequate water for the biogas digester can be collected from rooftops in tanks. The collection of water from roofs for household and garden use is widely practised across southern Africa. Tanks and containers of all types, from large brick reservoirs to makeshift drums and buckets, are a common sight in rural areas. The advantages of collecting water from roofs are that the roofs are physically in place and runoff is immediately accessible, the water collected from roofs is much cleaner than from land runoff, and most of the rainwater falling on the roof can be collected as there is little absorption or infiltration on the roof surface.

Various RWH technologies and biogas digesters are used at sites scattered around the country. However, there is no single rural village where an integrated approach to economic development based on fodder, food, energy and water security is used. This emphasised the importance of conducting an R&D project on the upscaling of rainwater and conservation on croplands and rangelands for food and renewable fuel (biogas) production.

The research project helped to answer the following questions:

- Can RWH&C techniques contribute to higher food production and improved livelihoods through increased crop and livestock production?
- Can cattle manure be used as a source of renewable energy through biogas production in rural communities?
- Can RWH&C contribute to an enhancement of ecological stability and improvement of biodiversity conservation in communal rangelands?
- Can RWH&C techniques and biogas production contribute to higher crop and livestock water use productivity?
- Can RWH&C technologies and biogas production be economically viable?

## 1.3 PROBLEM STATEMENT

Food insecurity in rural communities in the Eastern Cape is alarmingly high. This can partially be attributed to poor management practices (such as continuous cropping or monoculture-based systems, intensive cultivation and crop removal, which leave the soil bare and highly degradable) that are used by the smallholder farming sector. Monoculture-based cropping systems and intensive cultivation have given rise to soils that are characteristically low in terms of nutrients (especially nitrogen and phosphorus) and soil organic matter. Furthermore, the use of chemical fertilizers does not provide an appropriate solution, as the majority of smallholder farmers often lack sufficient funds to purchase such inputs in order to reclaim the fertility of the soil. The amount of mineral fertilizer applied by smallholder farmers is often far below the recommended application rates required to sustain reasonable crop yields. Lack of inputs, coupled with low and erratic rainfall, which result in low yields or total crop failures, has prevented many smallholder farmers or villagers from using their homestead gardens and croplands effectively for food production. Livestock production is therefore the main agricultural activity in many rural communities. However, livestock production is also low, due to the poor quality of the rangelands. There is no proper veld management system in place to improve the grazing capacity of the rangelands.

The poor production in rural villages has resulted in continued food insecurity, poverty and lack of saleable surplus. Therefore, the emphasis should be on improving production in the homestead gardens, crops and rangelands, without impacting negatively on the environment. Possible solutions to the problem might be the use of applicable RWH&C production techniques and the application of bio-slurry as an alternative to chemical fertilizers.

Bio-slurry is the residue (by-product) of the anaerobic digestion of manure to produce biogas. The bio-slurry can be used as a fertilizer for crop production, while the biogas can be used as a renewable energy source for cooking and heating purposes. Use of biogas will also address the problem of deforestation in rural communities where trees are chopped down and used as firewood to prepare food.

## 1.4 AIM

A realistic issue is that failure by the government to fund or invest in energy development will have dire problems to the people and economy as a whole. According to Trollip et al. (2014), over the past two decades, South Africa has failed to create the conditions for adequate investment in the major energy infrastructure developments that are required.

There is also a monumental backlog in infrastructure development and an apparent investment paralysis. While there have been some stopgap measures and a few successes, these are the exceptions. Even when definitive policy statements have been made at the highest level, implementation has been and remains problematic. This is evident in the shortages in bulk electricity supply, the growing backlog and ongoing deterioration of electricity redistribution infrastructure, poor household energy insecurity, discontinuities in coal supply, the absence of a credible liquid fuels policy and comparatively low crude oil stocks (Trollip et al., 2014). Therefore, in an effort to address energy and food insecurity, as well as health-related issues in the rural villages of the Eastern Cape, this project was conducted in selected villages. The aim was to upscale RWH&C practices on croplands and rangelands for food and renewable energy (biogas) production (Figure 1.1), which will improve the lives of the villagers without impacting negatively on either the soil or the environment.

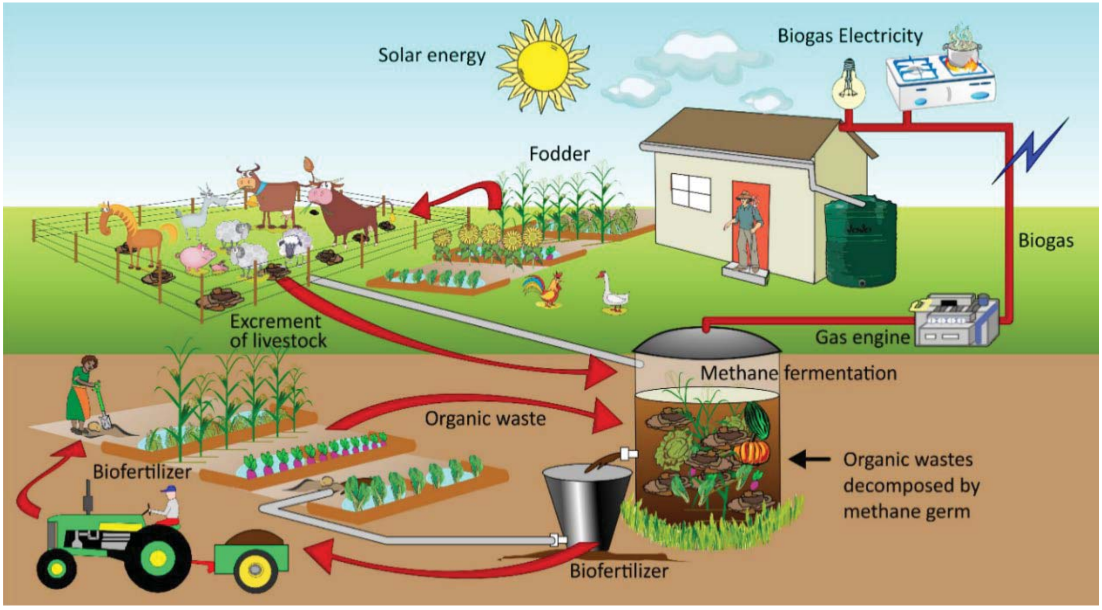



**Figure 1.1: Diagrammatic representation of the aim of the project**

For this project, biogas was used as an alternative and renewable energy source to provide for various applications, such as lighting, heating and cooking on a household scale. The residual material (bio-slurry) was used as a fertilizer (nutritional aspects for crops and soil) in an effort to reduce the costs of crop production.

The specific objectives of the project were the following:

- Do an in-depth literature review on RWH&C to improve production on homestead gardens, rangelands and croplands through functional institutional arrangements, as well as the application of biogas as a renewable energy source in semi-arid areas.

- Describe the natural and human resources, institutional arrangements, organisational structures and farming systems in the study area.
- Demonstrate and evaluate appropriate RWH&C techniques for increased crop and livestock production on homestead gardens, croplands and rangelands, with particular attention to biogas from cattle manure as a source of renewable energy at the household and/or village scale for a combination of food and fuel production systems.
- Investigate, understand and implement workable institutional arrangements through the rediscovery of previous functional and dysfunctional working rules for increased crop and livestock water use productivity for a combination of food and fuel production systems.
- Evaluate the social acceptability, and financial and economic feasibility of biogas generation to meet energy demands at household and/or village scale within appropriate institutional arrangements and organisational structures.
- Investigate best management practices of livestock (cattle) for manure collection and transportation to biogas digesters as a renewable energy source.
- Evaluate the suitability, effectiveness and possible practical application of biogas effluent as a liquid fertilizer.
- Assess, monitor and evaluate the quantity of roof water harvested and its use within the homestead for the production of biogas, crop production and domestic use.
- Evaluate rangeland rainfall use efficiency, water use efficiency and water use productivity, and the use of these parameters in determining rangeland water dynamics.
- Assess the communal livestock grazing patterns, production performance and livestock water productivity over different seasons and vegetation types.

## 1.5 LIMITATIONS

The project has experienced a number of problems, mostly beyond the control of the project team. Some of these problems and limitations experienced were the following:

- Provision was only made for the installation of two biogas production systems. This would have been inefficient to make any impact and to demonstrate the benefits of biogas production and the use of its by-product on a village scale. With financial assistance from the Eastern Cape's Department of Rural Development and Agrarian Reform, it was possible to implement 14 bio-digesters.
- Workmanship from contractors who initially built the bio-digesters was poor and digesters had to be reconstructed, which delayed the application of the bio-digesters and the bio-slurry. This resulted in some smallholder farmers and villagers (as beneficiaries) being discouraged, and they lost interest in the project, as they could not enjoy the anticipated benefits from the start of the project.
- There was no budget for the procurement of expensive measuring equipment to record biogas production and use. Results therefore had to be extrapolated from the test site at the University of Fort Hare.
- Municipal services in the study area have collapsed, so taps regularly ran dry. The little available rainwater that was collected in the tanks was used sparingly for domestic purposes instead of feeding the bio-digesters. This was detrimental to the bacterial growth necessary for a digester to operate effectively.
- Since running water was not always available, villagers filled the tanks with tap water whenever it was available. Water collected in tanks was therefore not a true reflection of the quantity and quality of water harvested from rooftops.
- Equipment to record all the parameters on the rangeland experiments and animal movement were either not available or only procured at a very late stage. Secondly, the loss of the team member leading the rangeland aspects became catastrophic for the project. Consequently, limited data was collected regarding the water use efficiencies in the rangelands and animal movement.

- Despite smallholder farmers and villagers being given data sheets to keep records of inputs, outputs and income from homestead gardens and biogas production, as well as water collection and usage from tanks, some failed to keep records, and information was unreliable.
- Initially, some smallholder farmers and villagers failed to implement and adhere to agreed institutional arrangements, especially those who owned livestock. This impacted negatively on the whole production system.
- Theft and damage to research equipment was by far the biggest problem experienced. In the rangelands, fencing from enclosure cages was stolen several times, allowing animals to graze in the excluded areas. Neutron water meter access tubes used to monitor the soil moisture content were also stolen. At the on-station experimental plots, where the cropland trials were conducted, neighbouring villages stole maize cobs before they reached physiological maturity. Fences were cut and stolen, and the gate was left open on several occasions to allow cattle to graze in the experimental plots and destroy the crops.
- The COVID-19 pandemic, which resulted in a nationwide lockdown, restricted movement of the project team members. They could not continue with their normal project activities.
- Changes in project team dynamics hampered the smooth running of the project. None of the project team members who led the biogas, rangeland and crop production components remained for the entire duration of the project. Where project team members changed constantly, it was difficult to gain the trust of the smallholder farmers and villagers.

## 1.6 LAYOUT

The report is presented in ten chapters and is structured in such a way to address the specific project objectives.

Chapter 1: Introduction with problem statement, motivation for conducting the project and project-specific objectives.
Chapter 2: Literature review on institutional arrangements, rainwater harvesting for crop production in homestead gardens and croplands, conservation of rangelands and rangeland water dynamics and biogas production (Objective 1).
Chapter 3: Site selection and description of the study area (Objective 2).
Chapter 4: Institutional arrangements for improved agricultural production (Objective 4).
Chapter 5: Evaluation of appropriate rainwater harvesting and conservation technologies for increased crop production at homestead gardens and croplands (Objectives 3 and 8).
Chapter 6: Conservation of rangelands for improved rainfall use efficiency, water use efficiency and water use productivity (Objective 9).
Chapter 7: Livestock grazing patterns and manure collection (Objectives 6 and 10).
Chapter 8: Biogas production and application of effluent as liquid manure (Objectives 3, 5 and 7).
Chapter 9: Conclusions and recommendations.
Chapter 10: References to the literature used.

# CHAPTER 2: LITERATURE REVIEW

## 2.1 PROJECT CONCEPTUALISATION

A project, initiated and funded by the WRC, was conducted over a period of five years (2015–2020) at the Krwakrwa and Upper Ncera villages near the town of Alice and at Fort Cox College in the Eastern Cape. The research team was a multidisciplinary team consisting of researchers, employees and students from the ARC-SCW (the lead organisation), the Eastern Cape Department of Rural Development and Agrarian Reform, Fort Cox College and the University of Fort Hare. The project aimed at assessing the upscaling of RWH&C practices on croplands and rangelands for food and renewable fuel (biogas) production that would improve rural livelihoods without having a negative influence on the environment. However, the sustainability of an integrated crop, animal and biogas production system depends heavily on the optimal functioning of all the components of the system (Figure 2.1). In a rural setting, household food security is the first priority. The homestead garden can be utilised for food production through the implementation of suitable crop production systems like IRWH. In order to eradicate hunger and poverty in rural villages, smallholder farmers and villagers will have to expand their production to the unutilised croplands, whereby they can produce maize (as a staple food), beans (as a protein source) and sunflower (as an oil source) on a larger scale. Low yields or crop failures are common in semi-arid areas where crops are produced under normal conventional tillage practices. However, sustainable crop production is possible through the application of suitable RWH&C practices.

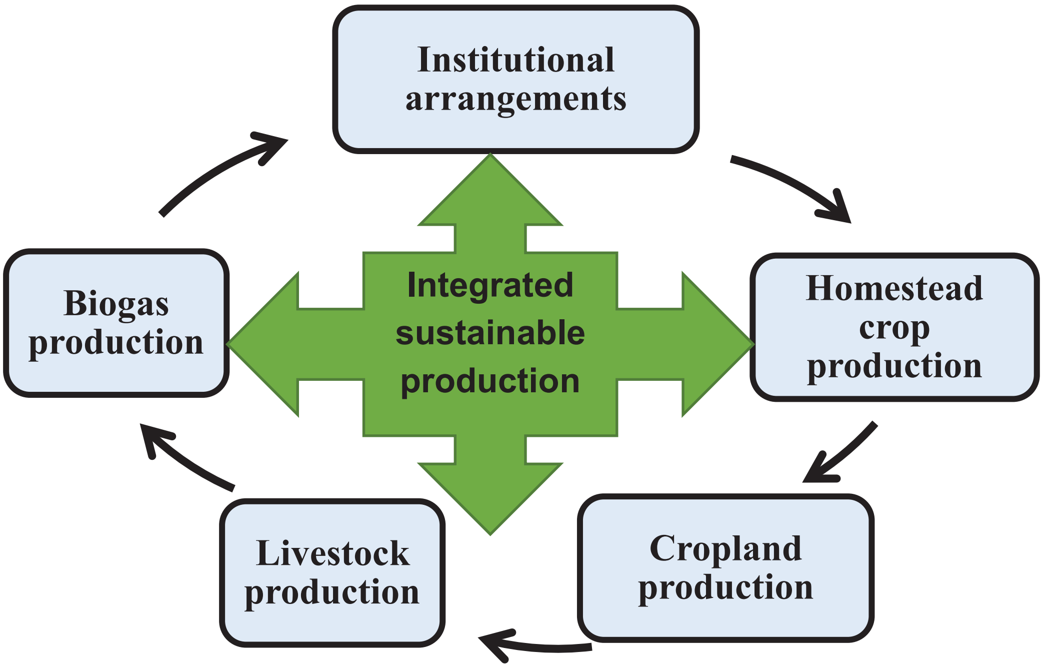



**Figure 2.1: Diagrammatic representation of the integrated production system**

Additionally, animal production has always been a priority in rural villages, since smallholder farmers and villagers not only measure their status by the number of animals they own, but also slaughtered animals for traditional ceremonies. There is usually no veld management system in place, and animals roam freely. This has resulted in overgrazing and poor veld condition. After field crops have been harvested, animals graze in the croplands where maize stalks are used as fodder for the animals. However, where, for example, IRWH structures were implemented in the croplands, animals should not be allowed because they can destroy the basin structures that were constructed.

As this can then be a source of conflict between animal and crop production farmers, it is important to have functional and workable institutional arrangements in place to ensure optimal production and benefit for both sides. Where biogas production is introduced into the current farming system, the effluent from the bio-digester can be used as a liquid organic fertilizer in the homestead garden, as well as the croplands and rangelands. In order to ensure maximum biogas production and high-quality slurry, the digester needs to be fed with manure of a good quality. Animals that are in a good condition and graze on veld of a good quality will produce good-quality manure as an input source for the digester. Again, functional and workable institutional arrangements need to be in place so that they can guide animal movement and the collection of manure. It was therefore critical to conduct a detailed literature review to gain a better understanding of the various components of the integrated production system.

## 2.2 INSTITUTIONAL ARRANGEMENTS

### 2.2.1 Introduction

Food production within the rural areas contributes to the nation’s economy, food security and quality of life in general. Agricultural production is a complex and dynamic network of both government, private and public entities. Many researchers believe attention to project design and institutional arrangements are vital in creating successful projects that involve smallholder farmers (Boyd et al., 2007; Corbera and Brown, 2008). They ensure security and perform economising functions (Lin, 1989). They create “order”. Therefore, they reduce “conflict” and ensure “mutual gains” (Williamson, 2000). They shield actors from potential hazards and reduce transaction costs associated with exchange (Klein, 2000; Kirsten et al., 2009). They furthermore play an important role in coordinating economic and social activities. When it comes to a definition, there is no single definition that completely covers the term, because it is used in many different forms and contexts. According to D’haese et al. (2005), analysis showed how new institutional arrangements may contribute to economic development. Botha et al. (2014b) have shown how non-adherence to institutional arrangements has impacted negatively on the food security and social wellbeing of rural communities in the Eastern Cape, Free State and Limpopo.

As part of the literature review, the next section covers the definition of institutional arrangements and why they are important. Moreover, for this report, institutional arrangements will be interpreted as the rules, norms and procedures that guide how people within society live, work and interact with each other. That further encompasses structures, approaches, practices or rules put in place by relevant stakeholders (traditional leaders, groups of people with a common vision, etc.) at all levels to steer development and growth, including for assessing impacts, vulnerability and risks, planning for progress and the implementation of measures that will see their common vision grow.

### 2.2.2 Defining institutional arrangements

Institutional arrangements are different formal and informal regimes and coalitions for collective action and inter-agent coordination, ranging from public-private cooperation and contracting schemes, and organisational networking to policy arrangements (Geels, 2004; Klijn and Teisman, 2000). Dorward et al. (2005) argue that the current emphasis in research and policy discussions on the institutional environment (such as property rights, regulations, policies and informal rules) in Africa is at the expense of sufficient attention to institutional arrangements. According to Monde et al. (2012), institutional arrangements are really an interrelated set of rules and regulations to enable coordinating activities to achieve social goals. Rendering the same sentiments, Eaton et al. (2008) and North (1990) define them as the rules, conditions and regulations designed for situations involving a subset of individuals or groups. Institutional arrangements are the combination of formal constraints and informal rules, and their enforcement characteristics (North, 2005).

Institutional arrangements are defined as the formal and informal rules and norms that define who has decision-making authority over a common resource (such as water) and the specific use, management, monitoring and enforcement decisions that are produced (Ostrom, 1990; 2005). As several studies have indicated that institutional arrangement affect human decisions and interactions, as well as economic performance and development, the need for improved institutional arrangements has been recognised for many years. Without effective institutional arrangements, a suitable environment to effectively deliver development policy cannot be created and will thus not succeed in tackling rural development problems (Hamzah, 2010). According to Lin and Nugent (1995), an institutional arrangement is a set of behavioural rules that governs behaviour in a specific domain. Institutional structure, on the other hand, is the totality of institutional arrangements in an economy, including its organisations, laws, customs and ideology (Hamzah, 2010).

The purpose of these arrangements is to prevent conflicts that are mutually damaging, and also to distribute entitlements, opportunities and public goods that are essential to individuals or groups, which they may not be able to access otherwise (Abraham, 2015). One thing for sure is that there is no single definition for institutional arrangements, and the term can be used in many different forms and contexts. For the sake of this report, institutional arrangements are interpreted as those structures, approaches, practices or rules put in place by smallholder farmers through the help of the project leaders and stakeholders at all levels to steer the rules and regulations governing production within the selected areas. These institutional arrangements include assessment, planning, implementation and M&E.

### 2.2.3 Why institutional arrangements?

The successful implementation of any project needs workable and functional institutional arrangements. They can help to better understand the main elements that can be conductive to an enhanced institutional setting, and therefore the better functioning of the public function. In this context, such reviews can enhance the transparency of processes and results. This, in turn, may create commitment to subsequent change: stakeholders can refer to concrete recommendations to improve different critical aspects, such as inter-ministerial coordination mechanisms, the implementation of strategic documents and the prioritisation and sequencing of activities. Vella (2003) mentioned that:

> *Formal and informal institutional arrangements give multiple users access to the same land resources to use the land for different purposes. For example, the use of outback and savannah landscapes is governed by a formal property rights system, which confers grazing and mining as the principal users, largely reflecting 19th century British landscape understanding and colonial objectives. These land uses have a degree of formal ownership over the resources they are using, extracting and managing, examples include the ownership of entitlements for grazing, irrigation or ownership of mineral resources for mining. Ownership of common pool resources and rights to use the commons are conferred to land users through institutional arrangements such as lease entitlements. In terms of natural resources, these land users have a relationship to the land, which is defined by three key elements: resource ownership, resource use and resource management.*

According to Pritchard and Bullock (2014), in order to enhance the likelihood of achieving the development objectives of a project, the delivery modalities and corresponding institutional arrangements need to be aligned with such goal systems. Pritchard and Bullock (2014) further state that a livelihood support project needs a different institutional delivery set-up than a typical value chain project. Changes in institutional arrangements are, however, likely to yield more concentrated and tangible benefits for defined groups. Additionally, these are often easier for individuals and groups to promote through negotiation between more manageable groups of stakeholders (in some cases with bilateral negotiations).

In order to be effective, institutional arrangements should not be designed as stand-alone structures, but should rather be conceptualised within a broader socio-economic (or even socio-political) framework within which they unfold (Eaton et al., 2008; Department of Provincial and Local Government, 2000). This implies that institutional arrangements should take into account various views of either villagers or individuals in order to remain relevant and legitimate to all. Upon agreeing to implement institutional arrangements, everyone should adhere to them to make sure that whatever they do is successful, and failure to follow them properly should lead to enforceable penalties. Appropriate institutional arrangements and good governance are important to the performance of enterprises initiated by groups of smallholder farmers (Chibanda et al., 2009). According to Helmer and Hespanhol (2007), good institutional arrangements are essential to liberate and develop resources further. Any effort to change institutional arrangements should begin with identifying the problems to be solved and the roles of the various actors engaged in water management – who does what, where, to what end and how well? Based on this analysis, gaps can be filled and coordinating mechanisms developed or strengthened.

According to the International Fund for Agricultural Development (2013), an effective project institutional arrangement is expected to have four pillars: institutional mechanisms and instruments used in project oversight for policy and strategic guidance, project management, the coordination of project partners and key stakeholders, and implementation arrangements for delivering project goods and services to beneficiaries. The International Fund for Agricultural Development (2013) further mentioned that a systematic process of assessment should guide institutional arrangements for project oversight, management coordination and implementation. This will help define an optimal institutional mix that will guarantee efficiency and effectiveness in delivering goods and services to project beneficiaries, ensure achievement of the intended results, and permit an evaluation of impacts and documentation of lessons learnt.

## 2.3 RAINWATER HARVESTING FOR CROP PRODUCTION

For a large proportion of the population in Africa, farming is a way of life and not a commercial activity. Therefore, ensuring food security represents a major challenge for the agricultural future in these areas (Kronen, 1994). In sub-Saharan Africa, food production depends almost entirely on rainfed agriculture. The scope for further irrigation development is limited as water resources are becoming increasingly scarce and the most suitable sites have already been developed (Kauffman et al., 2003). Therefore, these resources need to be conserved and used optimally. Water harvesting is particularly advantageous in optimally using rainwater in the following circumstances (Oweis et al., 2001):

- In dry environments, where low and poorly distributed rainfall normally makes agricultural production impossible. Provided other production factors, such as soils and crops, are favourable, water harvesting can make farming possible, despite the absence of other water resources.
- In rainfed areas, where crops can be produced, but with low yields and a high risk of failure. Here water harvesting systems can provide enough water to supplement rainfall and thereby increase and stabilise production.
- In areas where water supply for domestic and animal production is not sufficient. These needs can be satisfied with water harvesting.
- In arid land that suffers from desertification, where the potential for production is diminishing due to lack of proper management. Providing water to these lands through water harvesting can improve the vegetative cover and can help halt environmental degradation.

In many cases where the total rainfall may appear to be adequate for the production of particular crops, its intensity and distribution are of such a pattern that the water available during the crop growth cycle is inadequate to support a good harvest (Lövenstein, 1994; Ofori, 1994; Sow et al., 1996). In semi-arid regions, rainfed agriculture also generally has to cope with soil with a low potential (Fofana et al., 2003;

Stroosnijder, 2003). The problem of inadequate soil water is not only caused by low and unfavourable distribution of rainfall, but is even exacerbated by high unproductive water loss through evaporation from the soil surface, runoff and deep drainage (Arnon, 1975; Arnon and Gupta, 1995). These losses hamper the efficient use of available water for crop production, and need to be minimised in order to optimise rainwater productivity (RWP). The two main losses are evaporation from the soil surface and runoff. An attempt needs to be made to minimise these unproductive water losses. This can be achieved through various water harvesting techniques (Welderufael, 2006).

Water harvesting techniques aim to alleviate the most limiting crop production factors: water and soil fertility (Kronen, 1994). The principle of water harvesting is based on depriving a certain area of its share of rainwater, which would have been non-productive, and diverting it to another part of the land where it is more useful (Oweis et al., 2001). Since water harvesting is only one of the management practices whereby water availability to plants can be improved, Reij et al. (1988) gave the following definitions:

- Water harvesting makes use of and even induces surface runoff, whereas *in situ* water conservation aims to prevent runoff and retain precipitation where it falls.
- Water harvesting is restricted to methods that are entirely dependent on local rainfall, i.e. rainfed or dryland agriculture, in contrast to irrigated agriculture.

All water harvesting practices have three main characteristics in common:

- They are applied in arid and semi-arid regions to minimise runoff.
- They depend on local water such as runoff, springs or soaks and do not include damming river water or the use of underground water.
- They are small-scale operations in terms of catchment area, volume of storage and capital investment (Boers and Ben-Asher, 1982).

The catchment area is the part of the land that contributes some or its entire share of rainwater to a target area outside its boundaries. The catchment area can vary in size from only a few square metres to as large as several square kilometres. It can be agricultural, rocky or marginal land, or even a rooftop or a paved road (Oweis et al., 2001). In the absence of natural catchment surfaces such as rock, slopes or impermeable structures such as rooftops of buildings, runoff may be induced from a land catchment surface by implementing infiltration-reducing measures such as vegetation management, surface treatments (e.g. soil compaction) or chemical amendments (Boers and Ben-Asher, 1982). The storage facility is a place where runoff water from the catchment area is stored and held until it is collected for use. Storage facilities can be in the form of surface reservoirs, subsurface reservoirs such as cisterns, in the soil profile as soil moisture, and in groundwater aquifers (Oweis et al., 2001). The target area is where the harvested water is used. In agricultural production, the target is the plant or animal, while in domestic use the human or the enterprise is the target (Oweis et al., 2001).

Rainwater harvesting systems are divided into two main groups: macro and micro catchment systems (Oweis et al., 2001). The micro catchments are divided into two groups: on-farm and rooftop. On-farm catchment surfaces may be natural, with no vegetation modification; the soil surface can be cleared of vegetation or it can be treated with a substance to induce runoff. Rooftop catchments include rooftops of buildings, courtyards, road surfaces or any similar impermeable structures. An alternative classification system has been proposed by Van Rensburg et al. (2005), whereby water harvesting methods are categorised, simply according to the location of the catchment, as ex-field (runoff collected from outside the land boundary), in-field (runoff collected from within the land boundary) or non-field (e.g. rooftops).

Efficient water harvesting and conservation techniques for smallholder crop production can aid in alleviating poverty and helping farmers become self-sufficient. The lack of such techniques is a pressing problem for agriculture in semi-arid areas.

Water harvesting can aid smallholder crop farmers in utilising their low and erratic rainfall in order to grow sufficient crops to sustain their livelihoods (Kronen, 1994). Boers and Ben-Asher (1982) reported that, in addition to Australia, Mexico and the USA, water harvesting is practised on a limited scale in many countries throughout the Middle East, on the Indian sub-continent and in sub-Saharan Africa. According to Oweis et al. (2001), the West Asia and North Africa region played a key role in the development of ancient water harvesting techniques. Early structures in southern Jordan are believed to have been constructed over 9,000 years ago. There is evidence that simple water harvesting techniques were used in southern Mesopotamia as long ago as 4500 BC, while this kind of agriculture in the Negev Desert can be traced back as far as the 10th century BC.

Extensive research in South Africa has gone into developing a water harvesting system for growing crops in homestead gardens, although the focus is now shifting to implementing water harvesting in croplands at a much larger scale. This literature review aimed to review existing RWH techniques and determine the best techniques for use in homestead gardens and croplands.

### 2.3.1 Rainwater harvesting for homestead gardens

Home-grown or small-scale food production is a feasible contributor to food and nutrition security for the rural poor. Water scarcity remains a major threat to poverty, hunger alleviation, as well as sustainable development. Innovative water technologies, such as RWH, have the potential to improve rural water supply. RWH can also be the solution to South Africa’s food security by increasing the water productivity of dryland agriculture and enabling homestead gardening. Although used for decades in South Africa, RWH is still far from being utilised to its full potential as unresolved challenges prevent its wide-scale adoption. Key challenges that prevent the nationwide expansion of RWH are the current water-related legislations, inadequate financial support and a lack of national coordination. While opportunities lie in the value of knowledge gathered through research projects over the last two decades on the biophysical and socio-economic impacts of RWH and government buy-in (Kahinda and Taigbenu, 2011). Various RWH&C practices that can be applied in homestead gardens were identified from the available literature. Those that have the potential to be applied in the homestead gardens of the selected villages are described in more detail in the following sections.

#### Swales

Auerbach (1999) practices RWH in combination with conservation tillage and/organic farming in the steep areas of KwaZulu-Natal on the farm Bach’s Fen at the Rainman Landcare Foundation (Auerbach, 1999). He uses swales to retard runoff and promote infiltration, the retention of upstream sub-catchment and highway runoff in a wetland on the farm and pumping from this wetland to the gardens, mulches to reduce evaporation from the soil surface, and compost to increase the water- and nutrient-holding capacity of the soil. The value of the RWH measures is evident in the volumes of water available for use on the farm, which are dominated by the water-retention capacity of the wetland.

#### Trench bed gardening

According to Denison and Wotshela (2009), trench bed gardening was developed by Robert Mazibuko in the 1950s and 1960s in the Valley of a Thousand Hills (KwaZulu-Natal). Trench bed gardening is done by removing soil from the bed, usually 1 m wide, 2 m to 3 m long and 1 m deep. The topsoil is separated from the subsoil and mixed with manure or compost. Material is placed in a thick layer at the bottom of the trench and the soil is returned, topped by manure-rich topsoil, which is mounded above ground level (Denison and Wotshela, 2009). Trench bed gardening is usually combined with two other methods of RWH. The first is the diversion of water from surfaces adjacent to the garden into the beds by small cut-off channels. The second is the construction of small storage reservoirs (± 30,000 ℓ) for water collection from the roofs and the ground with augmentation by grey water (Denison and Wotshela, 2009).

**Roof top systems**

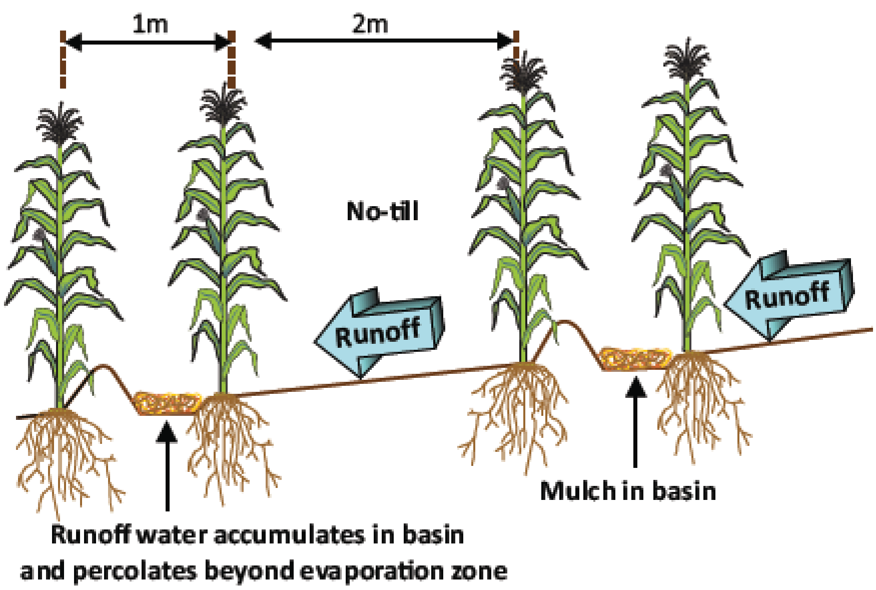
Rainwater can be collected from the roofs of houses and other buildings, as well as from other impermeable surfaces such as courtyards or roads, and stored in a tank. Such systems provide a low-cost water supply for humans and animals. Although mainly used for domestic purposes, the water that is unsuitable for drinking may be used for supplemental irrigation. Where biogas production is integrated in the production system, water collected in the tanks can also mixed with cattle manure to feed the bio-digesters.

**Homestead ponds**

Homestead ponds are associated more with cultivation and with conservation and irrigation (Denison and Wotshela, 2009). According to Denison and Wotshela (2009), the system of homestead ponds aimed to bring and concentrate water resources around homesteads and occasionally on agricultural land. Their construction was uncomplicated, although it involved sustained intensive labour. Homestead ponds were hand dug pits, mainly constructed with picks, hoes and shovels. They varied in both depth and diameter, although on average they were about 2 m deep and some 5 m in diameter. On occasion, some households erected stonework to support the walls and the bottom base against erosion during excessive flows. Water stored in the homestead ponds is used for supplemental irrigation to crops in the homestead, as well as for drinking water for the animals. Only a few of them are still in use in Thaba Nchu (Free Sate) and Tyhume Valley (Eastern Cape), especially due to their uncovered nature, which makes them dangerous for young children, as well as small livestock. The tragedy of children drowning led to homestead ponds being unused (Denison and Wotshela, 2009).

**In-field rainwater harvesting**

The IRWH technique was originally proposed in South Africa by Hensley et al. (2000) as an alternative to conventional crop production. It was designed to minimise unproductive losses due to ex-field runoff and evaporation from the soil surface. By combining the advantages of water harvesting, no-till, basin tillage and mulching on high drought-risk clay soils, the IRWH technique reduces runoff to zero and evaporation from the soil surface considerably. IRWH promotes rainfall runoff on a 2-m wide strip between crop rows, storing the runoff water in 1-m wide basins where it infiltrates deep into the soil below the surface layer, from which evaporation losses occur.



The results of six-year field studies conducted by Hensley et al. (2000) and Botha et al. (2003a) showed that IRWH produced significantly higher grain yield and RWP than conventional tillage, with yield increases averaging 40% for maize, 30% for sunflowers and 90% for dry beans. The IRWH technique proved to be agro-economically sustainable for crop production, as well as meeting the other requirements for sustainability. A further study on the benefits of mulching by Botha et al. (2003b) recommended that farmers should firstly apply mulch in the basins according to the IRWH technique, and if enough is available, in the runoff area too. The highest maize yields were obtained with organic mulch in the basins and stone mulch in the runoff area. The latter also helped prevent the movement of soil from the runoff area into the basins.

### 2.3.2 Rainwater harvesting for croplands

A large portion of the population lives in rural areas where their livelihood depends, directly or indirectly, on the agricultural sector. In these areas, the prominent challenges include land and water issues, old cultivation techniques, lack of information on marketing, poverty, the degradation of natural resources and environmental issues, population growth, inadequate support services, framework and institutional constraints, and lack of agricultural and rural development policies.

In rural villages in South Africa, most of the croplands have not been utilised for more than 20 years. Poor yields, a shortage of implements and lack of fencing have resulted in most croplands in the former homeland states being abandoned. A limited number of rural villagers are still making use of their conventional practices of producing mainly maize as their staple food. However, under these conditions, high water loss occurs due to runoff and evaporation from the soil surface, resulting in less water being available for crop production. The situation is aggravated by low and erratic rainfall and higher temperatures as a result of climate change. By applying efficient RWH&C techniques in communal croplands, smallholder farmers can alleviate poverty in their communities, which will help them become self-sufficient. However, the lack of such techniques is a pressing problem for agriculture in semi-arid areas. Various techniques for application in croplands were identified from the literature, of which only a few were deemed appropriate for use in semi-arid areas in the selected rural communities in South Africa. The identified techniques are discussed in more detail below.

**Contour ridging**

Contour bunds are a simplified form of micro catchments. Construction can be mechanised, and the technique is therefore suitable for implementation on a larger scale. As its name indicates, the bunds follow the contour, at close spacing, and by providing small earth ties, the system is divided into individual micro catchments. With contour bunds, crops or fodder can be cultivated between the bunds. As with other forms of micro catchment water harvesting techniques, the runoff yield is high, and when designed correctly, there is no loss of runoff from the system. With this technique, bunds or ridges are constructed on slopes along the contour line from 1 to 50%, usually spaced at between 5 and 20 m intervals. The first 1 to 2 m above the ridge is for cultivation, while the rest forms the catchment area. The height of the ridge varies from 0.3 to 1 m, depending on the slope gradient and the expected runoff storage capacity. Ridges may be reinforced with stones, e.g. on sandy soils, which are susceptible to erosion. The technique can be implemented by farmers using animal- or tractor-drawn implements. The accurate construction of ridges along the contour is of the utmost importance to avoid water flowing along it and accumulating at the lowest point. Alternatively, cross-bunds or tied ridges may be added at suitable intervals along the ridge. The contour ridge technique is the most important technique for supporting forages, grasses and hardy trees on gentle to steep slopes in low rainfall areas, while in the semi-arid tropics, it is used for arable crops such as sorghum and cowpeas. The technique is found in Botswana and Kenya, and is widespread throughout Burkina Faso (Oweis et al., 2001).

The successful implementation of this technique is based on the ability to locate the ridge as precisely as possible along the contour line. If this is not done successfully, water will flow along the ridge and accumulate at the lowest point, where it runs the risk of destroying the whole downslope system. If large stones are found in the area, stone bunds can be constructed on gentle slopes. Stone bunds are permeable, only slowing down sheet flow and promoting infiltration. Soil can be excavated and added to the upstream side of the bund to create an impermeable contour ridge (Oweis et al., 2001). The contour can be delineated by surveying instruments, an A-frame or hand tools, although these methods are too expensive, sophisticated and time-consuming for the average small-scale farmer.

**Tied ridging**

Tied ridging occurs when the ridges along the contour are closed with another shorter ridge. Box ridging is when shorter ridges are made at shorter intervals and not only at the end of each ridge. This creates a box effect, and the boxes then act as basins, which retain water (Kumwenda, 2003). Tied ridging is considered to be a very reliable method to increase crop yield and conserve water (Barry and Sonou, 2003; Mandiringana et al., 2003), although this technique has a high labour constraint. Due to the decrease in the use of animal draught power and the labour constraints among small-scale farmers, farmers have a negative outlook on this practice, which poses a considerable hindrance to its adoption and use by farmers (Barry and Sonou, 2003).

Tied ridges improved yields in drier regions by 19% and profit by 20%, whereas yields and profit in wetter regions improved by 49% and 43%, respectively. It was determined that, under high rainfall conditions, tied ridging is the best tillage practice for smallholder farmers (Mandiringana et al., 2003).

**Tied furrows**

Tied furrows are very similar to tied ridging, which allows for the concentration and conservation of water that results in good crop yields. Nyamudeza (1990) found that, on an experimental farm in Zimbabwe, grain yields increased by 49% on tied furrows when averaged over different population densities and row widths, compared with crop production on flat terrain. Nyamudeza (1990) reported that the tied furrow system increased rainwater use efficiency by 29%. A row spacing of 1.5 and 2.0 m had greater available water content than the traditional 1.0 m row spacing. This system is more effective on soil with a relatively high clay content, although such positive results do not occur on the more sandy soils, which exhibit poor fertility and water-holding capacity. Row spacing of 1.0 m, additional fertilizer and top dressing are the best compromise for these sandy soils when planting sorghum and maize according to the tied furrow system (Nyamudeza, 1990).

**Contour strip cropping**

Contour strip cropping involves alternating strips of crops with strips of grass or cover crops. The planted strips are used for cultivation. The uncultivated strips release runoff into the cultivated crop strips, thereby enhancing the soil water content in the area around the cultivated crops. The system has a two-fold advantage, as the cover crops can, in turn, be used for fodder production (Hatibu and Mahoo, 2000). The system is used on gentle slopes of up to 2%. The strip width can be adjusted to suit the gradient of the slope. The system is successful with a catchment area to crop basin area ratio of less than 2:1. The system is suited to most crops and is easy to mechanise (Hatibu and Mahoo, 2000).

**Runoff strips**

In the runoff strip technique, the area set aside for cropping is divided into strips along a contour. The technique is therefore suitable for gentle slopes. The upslope strip forms the catchment, while the downslope strip supports the crop. The downslope strip should ideally be between 1 and 3 m, and should not be too wide.

The size of the upslope strip will be determined by the amount of water needed (Oweis et al., 2001). Runoff strips can be fully mechanised. Therefore, the labour input is relatively low, although weeding and compaction may be needed to improve runoff. Good management and continuous cultivation of the strips can build up soil fertility and improve soil structure. Field crops such as barley are ideal for this technique (Oweis et al., 2001). If the slope is gentle and the cropped strip is too wide, the strip may not exhibit a uniform water distribution. Uneven moisture distribution can also occur if a ridge is formed along the upstream edge of the cropped strip during cultivation. To overcome this, the cropping strip should not exceed 2 m in width. In South Africa, Hensley et al. (2000) adapted the runoff strip system to include basins for runoff water storage in their IRWH technique.

**Inter-row system**

The inter-row system consists of bunds with a height ranging from 0.40 to 1 m, which are constructed at distances of 2 to 10 m apart, depending on the water requirement of the crop. These levees or triangular cross-sectional bunds are constructed along the main slope of the land, and are possibly the best technique to apply on flat lands. The bunds may be compacted, treated with water repellent or covered with plastic sheets to induce more runoff. Runoff is collected between the ridges and either directed to a reservoir at the end of a feed canal or to a crop cultivated between the ridges. High maintenance is needed in the catchment area to maintain a high runoff output (Oweis et al., 2001).

**Contour bench terracing**

The contour bench terrace technique is an excellent technique for soil conservation, as well as water harvesting, and can be constructed on very steep slopes. The cropping terraces are usually constructed level and supported by stone walls to slow down water flow and erosion. Steeper, non-cropped areas between the terraces supply additional runoff water. Excess water is safely removed with drains. This technique is mainly used for trees and bushes, and rarely for field crops. The construction and maintenance of such a system involves a high cost, which is not always possible for farmers in low rainfall areas (Oweis et al., 2001).

**Stone terracing**

According to Denison and Wotshela (2009), stone terracing is a simple RWH and management technique, but is labour intensive and is applied by only a few communities in the Eastern Cape and Limpopo. It is a historical practice that evolved largely through imported knowledge brought to South Africa by missionaries in the 18th century, combined with land pressure that forced people to move from the flatter, more fertile valleys (Denison and Wotshela, 2009). The practice has been modified over the years. It is a simple, but labour intensive RWH and management technique that is applied by only a few communities in the Eastern Cape and Limpopo (Denison and Wotshela, 2009). It involves the stacking of stones at the bottom of low-lying croplands. Stone walls are stacked high at the base of the slopes or downhill areas. Over time, these stone enclosures trap sediment that collects and contributes to the formation of new layers of soil. The technique has been used for planting various crops and trees (Denison and Wotshela, 2009).

**Bund systems**

The bund system consists of semi-circular earthen bunds that face directly upslope. The bunds are usually placed in staggered rows. They can also take the shape of a trapezoid or a crescent. They are created at a spacing that allows sufficient catchment to provide the required runoff water, which accumulates in front of the bund. Plants can then be grown in this area. The distance between the two ends of each bund varies between 1 and 8 m, and the bunds are between 0.30 and 0.50 m high. A slight depression is formed when creating the bund, where runoff is intercepted and stored in the root zone.

The technique can be applied on a level area up to a 15% slope. Bunds can be used for the rehabilitation of rangeland, fodder production, shrubs and, in some cases, field crops and vegetables like sorghum and watermelons (Oweis et al., 2001).

**Potholing**

Holes called potholes are made close to the planting stations or in between the planting stations. Rainwater is caught in these holes, which then increases the soil water content close to the planting station. The disadvantage is that the potholes fill up during the season and new ones need to be dug at the beginning of each season (Kumwenda, 2003). Mandiringana et al. (2003) conducted a study on potholing in the central Eastern Cape over the 1999/2000 cropping season. They showed that it was effective in water conservation and utilisation by plants, as reflected by an increase in yield compared to a control plot. This technique, like tie ridging, has a high labour constraint, and due to the decrease in the use of animal draught power and the acute labour constraints among small-scale farmers, farmers have a negative outlook on these practices. This poses a considerable hindrance on the adoption and use of these techniques by farmers (Mandiringana et al., 2003)

**Deep pits and pits**

Pits are a system of trenches on soil with a very low infiltration rate. The difference between deep pits and pits is the size and the crop. Trenches are dug across the slope and then filled to the original level using local fractured rock, river sand or organic material to ensure a high infiltration rate. These trenches collect rainfall, intercept runoff and store water in the surrounding area. In the Eastern Cape, trenches were dug 1.2 m deep or until a hard layer was reached. After being filled with organic material, earthen bunds were constructed around them to prevent water from spilling over. This combination of pits and bunds is excellent for the rehabilitation of agricultural land. Pits are usually 0.3 to 2 m in diameter. In Burkina Faso, the pits are dug to a depth of 0.05 to 0.15 m, and manure and grasses are mixed with some of the soil and added to the pit. The rest of the soil is used to form a small dyke on the downslope side of the pit (Oweis et al., 2001). A similar system is used on hillsides in southern Tanzania where the pits and bunds are used on an alternating basis for the production of maize, wheat and beans. One-year seeds are planted on the heaps, and the following year they are planted in the pits. This system is effective in preventing erosion because any overflow from one pit is trapped in the next pit. The system maintains soil fertility as the plant residues are thrown into the pits (Ley, 1990). Deep pitting is used for deep-rooted perennial crops like trees, while pitting is mainly used for the cultivation of annual crops such as millet, maize and sorghum. There is a high labour requirement, especially during the first few years. After tillage, the pits have to be restored. If the area is flat, pits are regarded as *in situ* moisture conservation rather than water harvesting (Ley, 1990; Oweis et al., 2001).

**Small runoff basins**

The small runoff basin technique consists of small diamond- or rectangular-shaped structures surrounded by low earthen bunds. The long diagonal of the diamond or rectangle is situated parallel to the slope so that runoff flows to the lowest corner in which planting takes place. The negarim, 0.05 to 0.10 m in width and 0.10 to 0.25 m in length, is best for even ground, although almost any slope less than 5% can be used. Slopes above 5% could cause soil erosion and the bund height should be increased. Small runoff basins are most suitable for growing tree crops, although the soil should be deep enough to hold sufficient water for the whole dry season. Negarims have a positive effect on soil conservation and do not need high maintenance (Oweis et al., 2001).

**Swales**

Swales are defined as long, level excavations that can vary greatly in width and treatment from small ridges in gardens, rock piles across the slope, or deliberately excavated hollows in flat lands and low-slope landscapes.

These structures are usually vegetated, with trees or reeds planted on the crest of the swale. Auerbach (1999) reports that Vetiver grass is effective when planted on swales. The effect of the swale is to catch water that falls on the area above the swale, and to slow the water down, maximising infiltration. The vegetation on the crest holds the soil of the swale in the event of intense rainfall causing runoff flow to overtop the swale. The swale also creates a moist micro climate in the furrow above the swale wall. This often becomes highly productive, as plant-available moisture is much greater in this area. Swales are different to the contour bunds that are commonly erected in soil conservation programmes. Soil conservation aims to remove water from the field without damage to the soil, whereas swales promote water infiltration. Many large swales were constructed in Tennessee, USA, to combat "dustbowl" degradation under President Roosevelt's conservation and job creation programme, and are still functioning effectively (Mollison and Slay, 1991).

**In-field rainwater harvesting**

The ARC-SCW team at Glen, near Bloemfontein in the central Free State, developed manual IRWH, which Hensley et al. (2000) described in detail. The technique proved to be sustainable and outperformed conventional tillage due to the total stoppage of ex-field runoff and minimising evaporation from the soil surface (Botha et al*.,* 2003a; Botha, 2006; Anderson, 2007). Apart from increasing crop yield due to the better utilisation of rainwater and increased RWP, it also stops erosion (Hensley et al., 2000; Botha, 2006). Botha (2006) described the successful uptake of this technique in homestead gardens.

IRWH combines the advantages of water harvesting, no-till, basin tillage and mulching on high-drought-risk clay and duplex soils. During a rain event on these soils, the IRWH technique collects runoff from a 2 or 2.4 m wide no-till strip between alternative crop rows, and stores the runoff water in the basins, where it can infiltrate deep into the soil beyond the surface evaporation zone. After the basins have been constructed, no-till is applied to the land. Since the runoff area is not cultivated, a crust forms, which enhances runoff.

This innovative RWH technique has the potential to reduce total runoff and minimise evaporation from the soil surface considerably when implemented correctly. The result is increased plant-available water and thus higher yields. The advantages of IRWH are as follows:

- Basin tillage minimises runoff from the land.
- Water harvesting from the untilled, crusted soil on the 2 or 2.4 m wide intercrop row area serves to promote and concentrate runoff water in the basins. This promotes the infiltration of water beyond the surface evaporation zone and therefore minimises evaporation from the soil surface losses.
- Mulch on the runoff area contributes to minimise evaporation from the soil surface and prevents erosion or soil movement.

Several researchers in South Africa have investigated the concept of RWH. Hensley et al. (2000) started the basic concept of IRWH with a runoff area to basin area ratio of 2:1, which was tested on wheat, sorghum, sunflower and maize in the Free State. The technique was successfully extrapolated to 42 communities in the Thaba 'Nchu area (Botha et al., 2003b). Since then, research was conducted to clarify the dynamics of IRWH. Walker and Tsubo (2003) used the runoff data of Hensley et al. (2000) to develop a procedure for estimating rainfall intensity and an empirical relationship of the rainfall-runoff process. Zere et al. (2005) tested a procedure to estimate runoff and Tesfuhuney et al. (2013) tested various runoff strip lengths and the effect of mulch on runoff. Mzezewa and Van Rensburg (2011) and Tesfuhuney et al. (2013) addressed the rainfall intensity and runoff-rainfall relationship. Bothma et al. (2012) documented the role of soil physical properties on the rainfall-runoff relationship. Zerizghy (2012) investigated the evaporation from the soil surface on the runoff area during a fallow period. The mechanisation of IRWH would be ideal on croplands compared to the small areas of homestead gardens. Anderson and Botha (2009) and Van Rensburg et al. (2012) have attempted to address the mechanisation of the IRWH technique.

A furrow and basin plough are used to construct the mechanised IRWH structures. The furrow plough creates a 20 cm high contour ridge with a slope tending towards zero. The basin plough creates a basin 10 cm deep and 1 m wide every 1.5 m along the ploughed contour.

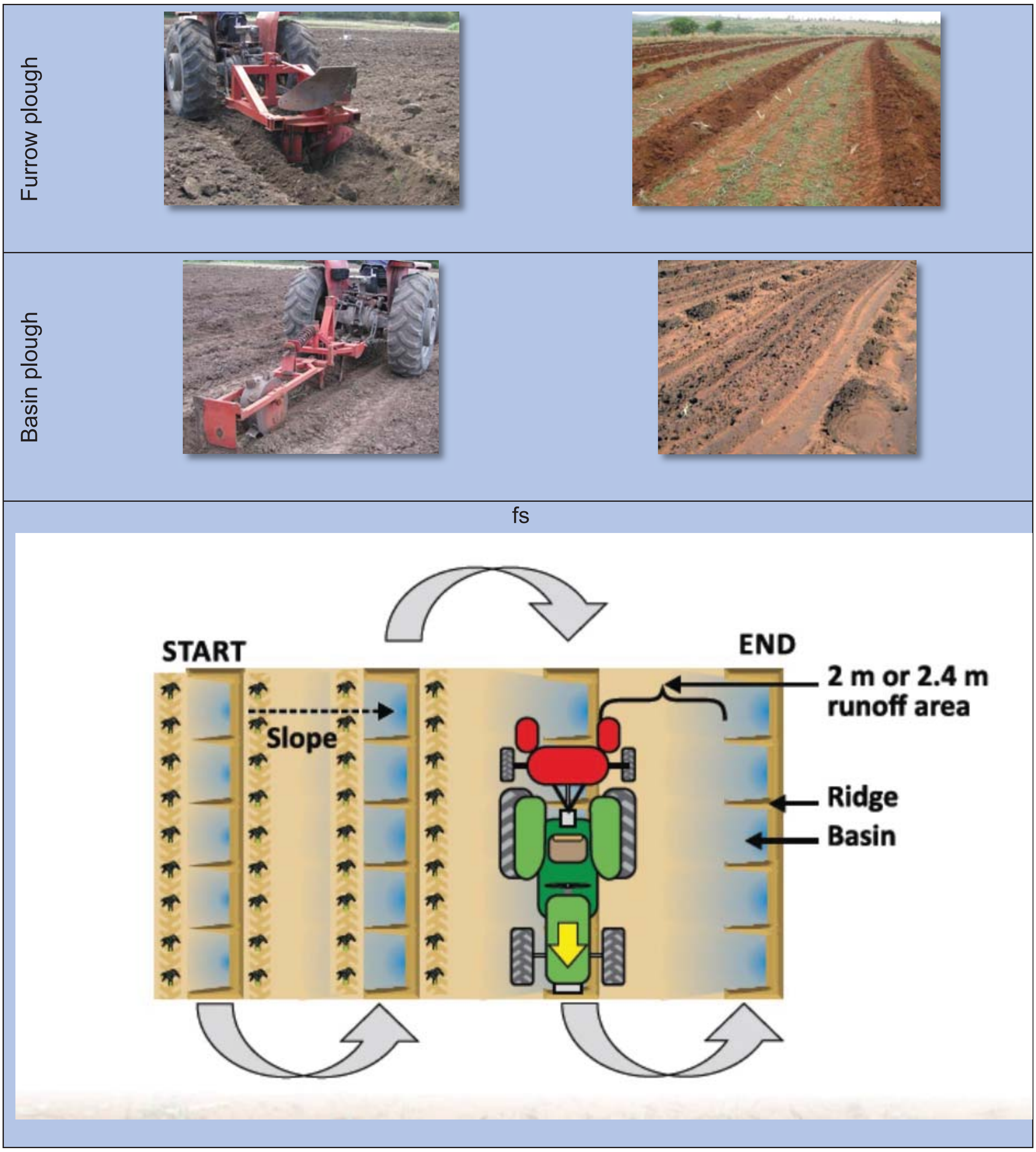



**Figure 2.3: Manual construction of in-field rainwater harvesting structures**

Van der Merwe (2005) tested the mechanised basin plough on clay soil in the Bafokeng district of North West, and found that it increased maize and sunflower yields compared to conventional tillage due to its better water conservation ability. Small basins in rows conserve the rainwater that falls into the basins, where the water can infiltrate deeper into the soil, below the evaporation layer. The mechanised basin technique does not have the ability to harvest additional runoff water.

The mechanised basin plough has a basin attachment (a small sharp scraper blade), which pivots on the rear of a three-point hitched ripper. The ripper tine operates directly in front of the attachment to break up compacted soil. The scraper at the rear of the attachment creates the basins. The diamond-shaped wheel controls the movement of the scraper blade, resulting in a row of basins being created. The distance between the basin rows is versatile and depends on the planter, application and maintenance actions. A 1 m spacing is recommended. A tractor wheel of 480 mm implies that, during implementation, the tractor returns on its tracks when implementing a new row, but the return trip must start about 50 mm away from the initial wheel tracks.

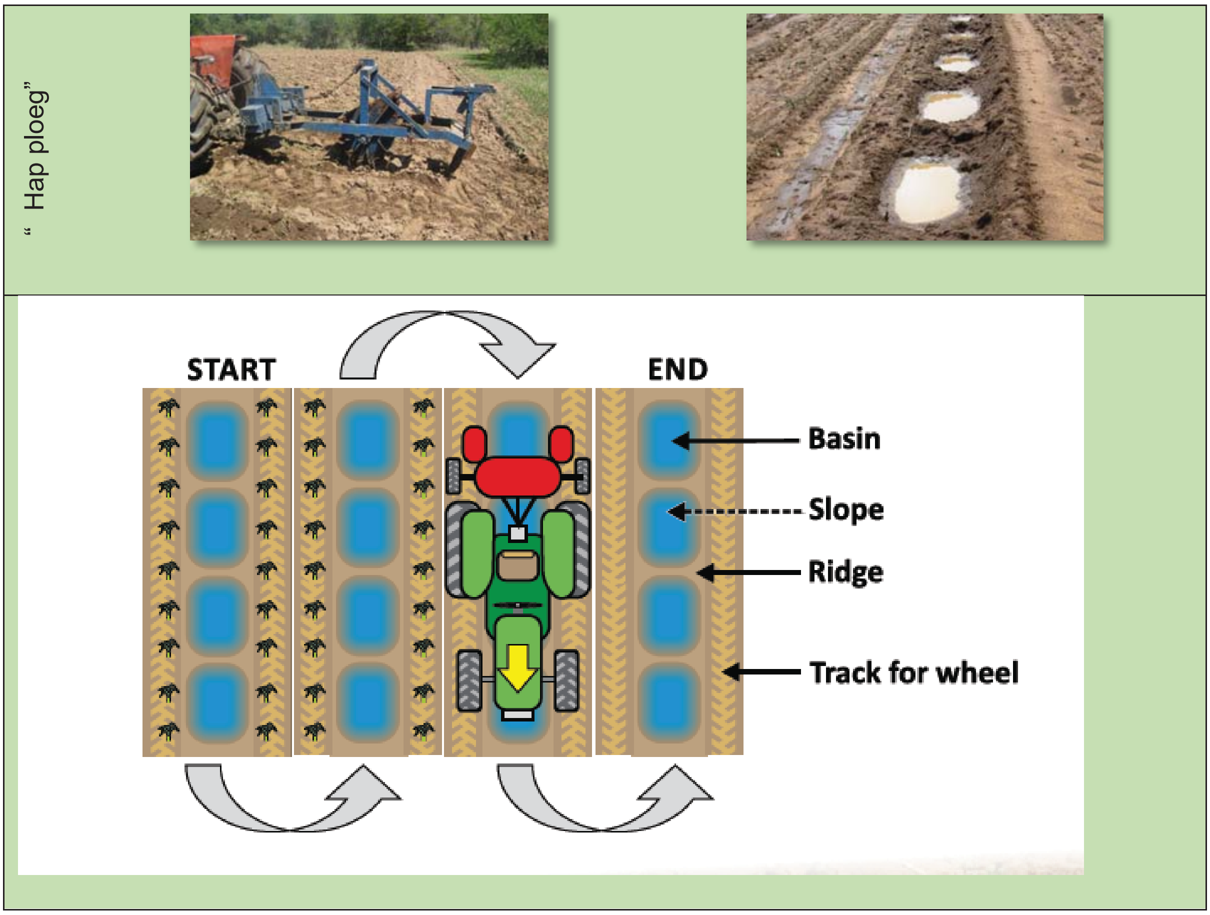



**Figure 2.4: Implementation and application of mechanised basins**

**Daling plough**

Mr Daling, a farmer near Settlers in Limpopo, developed the Daling plough. This plough creates a 1.8 m runoff area with a relatively wide and shallow basin. The Daling plough consists of a chisel plough in front, followed by a large V-shaped scraper blade with an off-centre wheel. The chisel plough is connected directly to the three-point linkage of the tractor. The large V-shaped scraper blade follows directly behind the chisel plough. The chisel plough first loosens the soil before long V-shaped or chevron-shaped basins are constructed. The off-centre rotating wheel lifts the scraper over the soil in front of the scraper so that it is left as a ridge (Anderson and Botha, 2009).

The Daling plough is based on the same principles as the IRWH technique, with the exception that no sunken basins are created. The Daling plough scrapes the top layer of the soil without changing the natural slope and applying large ridges on both sides of the large scraper blade. V-shaped basins are created. The chisel plough prepares a fine seedbed, while the scraper blade enhances runoff towards the lower point of the basin.

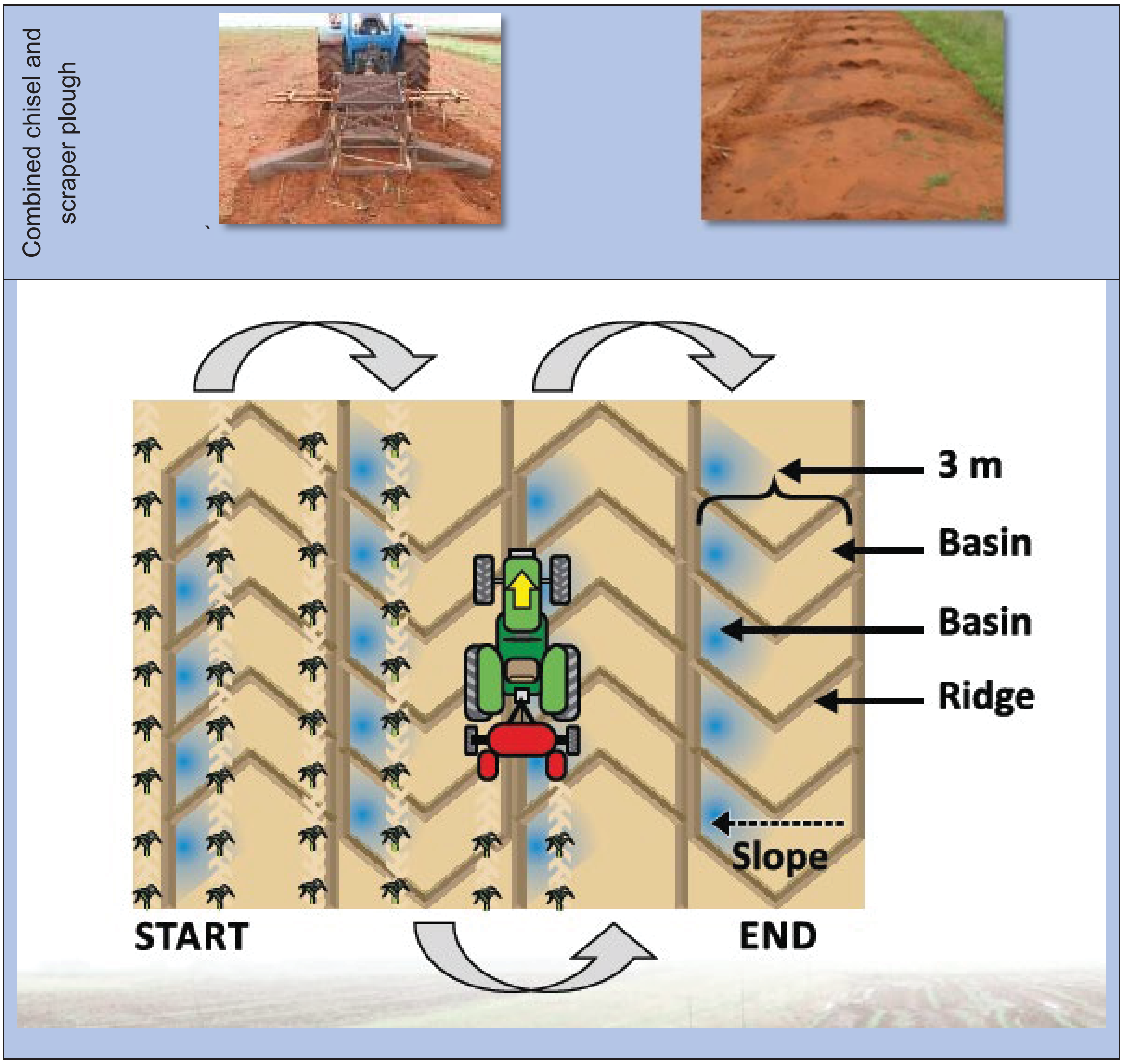



**Figure 2.5: Implementation and application of the Daling plough method for RWH in croplands**

**No/minimum tillage**

No-till and minimum tillage are conservation techniques that reduce the negative impact of rainfall on the soil via the crop residues on the soil surface. Since the consequence is less runoff and improved infiltration of rainwater, these techniques are seen as a form of RWH. Minimum tillage is a tillage practice that minimises mechanical soil disturbance and thus conserves water in the soil profile. Minimum tillage can vary from rip on the row with controlled traffic to only one primary tillage/cultivation, followed by chemical weed and disease control. With no-till, croplands are not tilled at all.

### 2.3.3 Summary

Water harvesting techniques have been employed in arid areas of the world for many years to maximise the use of limited and erratic rainfall, and are particularly well documented for sub-Saharan African, North African and West Asian countries. For example, the comprehensive review by Oweis et al. (2004) documents in detail the indigenous water harvesting systems found in Egypt, Iraq, Jordan, Libya, Morocco, Pakistan, Syria, Tunisia and Yemen, many of which have been in use for centuries. However, relatively few research studies appear to have been conducted to quantify the effectiveness and sustainability of these techniques. Of the studies that have been done, some have concentrated on water harvesting for supplemental irrigation and domestic use, leaving very few to have focused on micro catchment techniques as such.

Although water harvesting has been practised in South Africa for many years, especially indigenous systems, it has not been well documented until recently. The importance of water harvesting in South Africa has increased over the past few years, and more interest has been shown as the technology has received greater attention. By far the most detailed research has been conducted on the IRWH technique by Hensley et al. (2000) and Botha et al. (2003a). IRWH has been implemented with great success by smallholder farmers on marginal clay soils in the Free State, where it has proven to be agro-economically sustainable (higher crop yields), to reduce the risk of crop failures, to conserve the natural resources (no soil erosion), and to be economically viable and socially acceptable. Botha et al. (2003a) claim that the IRWH technique is a tool to empower people to fight food insecurity and poverty. With this in mind, it was decided to extend it to the Eastern Cape and Limpopo, and even to neighbouring countries (Botswana and Zimbabwe). However, given the fact that water conservation techniques are ecotope-specific, and given the limited extent of proven research studies on the suitability of specific methods under different conditions, it will be necessary to evaluate the benefits of any such technique when implementing it at a new locality.

The application of suitable RWH&C practices can be used successfully to improve crops yields and RWP in homestead gardens and croplands compared to conventional tillage/farmers' practices. This is especially important for production in semi-arid environments, where optimal use of every drop of rainwater is needed to produce food as effectively as possible. Cropland food production using appropriate RWH&C techniques could make a significant impact on food security through the ability of villagers to buy food with the money obtained through the sale of their excess produce. Where villagers have used basic handheld tools to construct RWH structures in their homestead gardens, they were also able to produce a variety of vegetable crops for their own consumption (Botha et al., 2007).

## 2.4 BIO-SLURRY AS A FERTILIZER SOURCE

Bio-slurry is the secondary or by-product that results from animal waste-based biogas plants. It has superior nutrient qualities when compared to the usual organic fertilizer, cattle dung, as its nitrogen is in the form of ammonia (Vaid and Garg, 2013). This is due to the fact that anaerobic digestion transforms nutrients from an organic state contained in the feedstock to mineralised states (an inorganic form) in the bio-slurry through a number of bacterial consortia, making them more readily available for plant uptake. It is a less costly and a more affordable fertilizer for smallholder farmers. As such, when it is recycled back to the soil, it promotes the recycling of essential nutrients, thus reducing costs to the household. Moreover, it enhances aggregate stability, improves aeration and drainage by adding soil organic matter, as well as plant essential nutrients like nitrogen (N), phosphorus (P) and potassium (K) (Nkoa, 2014). The amount of nutrients that are obtainable from bio-slurry as a soil amendment is influenced by the method and timing of application, soil physio-chemical properties, crop type, method and storage of manure, prevailing weather conditions during the time of application, the type of feedstock and the volume of water added or lost from the feed (Singh et al., 1996; Lukehurst et al., 2010; Makadi et al., 2012).

In terms of application method, bio-slurry can be applied to croplands in composted, dried or liquid form. In the liquid form, it can be applied using a bucket or discharging it through irrigation systems. However, application through irrigation systems is an expensive proposition for smallholder farmers, especially in the Eastern Cape, who have limited access to such resources. Hence, in its liquid form, it is preferably applied to homestead vegetable gardens, which are in close proximity to the bio-digesters. However, surface application of liquid bio-slurry complicates tilling operations and increases the probability of nitrogen loss through volatilisation as ammonia ($NH_3$). Therefore, in order to maximise fertilizer efficiency, it is recommended to apply bio-slurry in a dry form. It is the most preferred form by farmers when it relates to crop production, due to its easy handling and transportation. However, during the drying process, about 90% of nitrogen contained in the bio-slurry can be lost, thus reducing its value as a soil amendment.

**Nutrient content of bio-slurry**

Al Seadi (2008) reported that the amount of nutrients contained in the bio-slurry and their eventual uptake by plants varies from farm to farm. Moreover, nutrient availability from bio-slurry is influenced by the method and timing of application, soil physio-chemical properties, crop type, method and storage of manure, prevailing weather conditions during time of application, type of feedstock or digester and volume of water added or lost from the feed (Singh et al., 1996; Lukehurst et al., 2010; Makadi et al., 2012). Since bio-slurry is an organic fertilizer, the availability of nutrients for the growing crops is highly influenced by the activity of soil microbes, rate of mineralisation, soil pH and temperature (Chiyoka, 2011).

Bio-slurry is regarded a good source of nutrients as an organic fertilizer as it contains considerable amounts of both macro (nitrogen, phosphorus and potassium) and micro nutrients (zinc, manganese and boron) that are essential for plant growth (Alam, 2006). However, the amount of nutrients contained in the bio-slurry does not change much from that of the manure that is used as a feedstock. Hence, its application has the potential to improve soil structure and aeration, enhance water-holding capacity and diversify the nutrient base for a more sustainable crop production system (Yu et al., 2010). Furthermore, decomposition of organic matter during the digestion process enhances the bio-slurry's nutrient content when compared to other organic sources like manure on a dry weight basis (Möller and Müller, 2012). As such, anaerobic digestion tends to increase the amount of readily available nitrogen in the form of ammonium-nitrogen ($NH_4$-N) as a result of the nitrogen concentration effect when nitrogen is preserved and methane ($CH_4$) and carbon dioxide ($CO_2$) are formed (Tambone et al., 2009). The increased amounts of readily available nitrogen during anaerobic digestion means that the fertilizer value of bio-slurry is based on its nitrogen availability to the growing crop. As such, the availability of nitrogen in the bio-slurry is influenced by the carbon to nitrogen (C:N) ratio, pH value, inorganic nitrogen, method and timing of application, physio-chemical properties of the soil and the digestion process. Möller and Müller (2012) carried out a study to compare digested and undigested manures. They reported that digested material obtained from various feedstocks generally had a higher content of ammonium to total nitrogen ratios, decreased carbon content, reduced biological oxygen ($O_2$) demands, elevated pH values and lower C:N ratios.

Phosphorus is an important component of nucleotides, amines, proteins and phospholipids, and is thus an essential plant macro nutrient. Generally, crop availability of phosphorus is essentially influenced by changes in soil pH, which also influences its solubility. Similarly, the accumulation of volatile fatty acids (VFA) during anaerobic digestion tends to increases the pH of the bio-slurry relative to the manure that is used as a feedstock, which seems to reduce the amount of dissolved phosphorus.

**Effect of bio-slurry on crop growth**

In general, biogas effluent provides an efficient nitrogen source for plants with the potential to enhance crop yield and soil properties (Smith et al., 2014). When it relates to the crop nitrogen dynamics of bio-slurry, availability of nitrogen is highly influenced by its chemical composition and by the amount of nitrogen that can be lost following field application.

Furthermore, the anaerobic digestion process increases the content of $NH_4^+$-N, the stability of residual organic matter, and extensively lowers the C:N ratio, which results in an output with a large fraction of nitrogen that is readily available for plant uptake (Webb et al., 2013). The lowered C:N ratio of most feedstocks can be explained by the evolution of carbon as methane and carbon dioxide. Thus, the low C:N ratio in biogas residue leads to decreased nitrogen immobilisation, and consequently, enhanced nitrogen mineralisation and bio-availability at the time of application when compared to undigested manure. Therefore, it is imperative to consider the C:N ratio when determining the crop nitrogen requirement because nitrogen could be immobilised (through the incorporation of ammonium and nitrate to the soil biomass) in materials with high C:N ratios (>18) upon application to the soil. In light of the above findings, it is evident that bio-slurry has more potential to supply large amounts of nitrogen for crop uptake when compared to livestock manures, especially if ammonia losses and nitrate ($NO^3$-) leaching can be minimised through the correct timing of the application and immediate incorporation into the soil (Loria et al., 2007; Odlare et al., 2008; Gunnarsson et al., 2010; Cavalli et al., 2012).

A number of studies on bio-slurry have revealed that it can sustain high crop production (Walsh et al., 2012; Abubaker et al., 2012). However, some studies have reported no significant differences in crop yields on plots amended with bio-slurry and untreated manure. At the same time, some experiments have demonstrated that bio-slurry can have positive effects on crop yields.

A study by Odlare et al. (2008) reported that biogas residue obtained from source-separated household waste contained equivalent quantities of mineral nitrogen to that supplied by organic fertilizers of agricultural crops, and enhanced both the crop yield and grain quality of oats and spring barley. Garg et al. (2005) observed an increase in the grain yield of wheat on plots amended with bio-slurry produced from cattle dung over non-modified plots. The authors attributed the increase in yields to increased moisture retention, increased hydraulic conductivity and lower bulk density.

In a maize monoculture, Sieling et al. (2013) revealed that nitrogen use efficiency (NUE) was high or similar to that of mineral fertilizer, whereas low and similar values to pig slurry were obtained in perennial rye grass. In general, the response of agricultural crops fertilized with bio-slurry is better when compared to cow manure, pig slurry and mineral fertilizer (Odlare et al., 2008). Therefore, interest on how effectively biogas residue can substitute artificially produced synthetic mineral fertilizers in terms of crop yields is of paramount importance, especially if proper application methods are adhered to so as to maximise its value as a bio-fertilizer.

**Application method and form of bio-slurry**

Application method of bio-slurry is an important component that ensures that the desired results are obtained from using it as a soil amendment (Al Seadi, 2008). However, in its simplest form, due to its possible phyto-toxicity, high-cost application methods, viscosity and odour, and tedious handling, it might not be a suitable soil conditioner. Bio-slurry can be applied to croplands using a bucket or discharging it through irrigation systems, which creates complications as most farmers have limited access to such resources.

Applying bio-slurry in its liquid form complicates tilling operations and makes it difficult to transport it to farms that are far from the biogas plant. When applied in its liquid form, it is recommended to mix the bio-slurry with water in a 1:1 ratio so as to avoid any toxic effect on plant growth caused by high concentrations of accessible ammonium and soluble phosphorus. However, composting (aerobic degradation) and/or air drying of the bio-slurry is recommended to maximise its fertilizer use efficiency when applied to croplands and before it can be used as an acceptable saleable product.

During the drying process, most of the nitrogen contained in the bio-slurry is ammonium-nitrogen. About 90% can be lost through volatilisation as ammonia-nitrogen, thus reducing the value of bio-slurry as a crop fertilizer.

Additionally, the amount of dry matter (DM) contained in the manure has great influence on the extent at which $NH_3$ is emitted. Hence, cattle slurries with a low dry matter content can easily permeate the soil when compared to slurries with a higher dry matter content.

About 10% of $NH_4$-N in the bio-slurry is lost when it is applied on the field (Terhoeven-Urselmans et al., 2009). Therefore, volatilisation of nitrogen in the form of ammonia nitrogen (N-$NH_4$) also becomes a serious concern for farmers when bio-slurry is applied on the soil surface (Lukehurst et al., 2010). Notably, the best application method for bio-slurry is to apply it directly to the soil so as to limit any loss into the atmosphere (Al Seadi, 2008). Emissions of $NH_3$ can also cause an environmental hazard by increasing soil acidity through the nitrification process to nitric acid (Quakernack et al., 2012).

It is generally recommended that bio-slurry be incorporated into the soil within 12 hours of field spreading before nitrogen is lost as $NH_3$ (Möller and Stinner, 2010). Notably, $NH_3$ losses occurred within two days of field spreading, which the authors attributed to a soil-restricting layer caused by frozen soil, which could have limited the infiltration of most of the applied bio-slurry. They concluded that the use of bio-slurry as a soil amendment should follow thorough agricultural management.

Möller and Stinner (2009) carried out a study to evaluate the effect of bio-slurry on soil nitrogen mineral content in spring and autumn, to compare the $NH_3^+$ volatilisation of different manures from surface application to a cereal crop and to quantify greenhouse gas emissions within the whole stockless organic cropping system. The researchers revealed that there was a greater amount of $NH_3^+$, which was lost through volatilisation, on plots that were amended with bio-slurry than on plots with undigested slurry. The authors attributed their findings to the higher content of ammonia and pH. From these studies, it is apparent that, in order to maximise the fertilizer value of bio-slurry, time and application method is of the essence, as immediate use enhances its benefits.

**Application rate of bio-slurry**

The excessive application of fertilizers on crops can be perilous if too much fertilizer is applied to arable lands. As such, when appropriate application rates are adhered to, plants' physical characteristics and yield components are expected to increase (Reddy et al., 2003). When organic fertilizers such as livestock manure are applied at the recommended rates, they have great potential to provide nutrients and sustain crop yields, as well as the fertility of the soil (Al Seadi, 2008). Similarly, bio-slurry has great potential as an organic fertilizer, but there is limited knowledge about its nutrient release patterns and the factors that affect them, especially from a South African context. As a result, information on phosphorus release patterns and the application rates of bio-slurry are very limited (Chiyoka, 2011).

Excessive application of nitrogen can lead to high ammonia emissions, which may cause high environmental risks. Loss of ammonia that results from field applications does not only result in financial loss through fertilizer nitrogen loss, but $NH_3$ volatilisation is regarded as one of the major causes of atmospheric pollution by $NH_3$. Consequently, when too much $NH_3$ is deposited from the atmosphere, it can cause soil acidification and eutrophication of nitrogen-limited natural and semi-natural ecosystems, as well as surface water bodies. As the $NH_4^+$-N content of the bio-slurry increases, as well as the pH due to anaerobic digestion, it gives rise to evaporative $NH_3$ loss (Loria et al., 2007). This creates high potential for $NH_3$ emissions after bio-slurry application to croplands.

It has been generally reported that optimal application under irrigated fields is 10, 15 and 20 t $ha^{-1}$ and 5 t $ha^{-1}$ under rainfed conditions in order to achieve any meaningful yields (SNV, 2011). Similarly, Garg et al. (2005) reported that when bio-slurry was applied at 15 t $ha^{-1}$, it enhanced wheat yields by 6.21 t $ha^{-1}$ compared to 5.17 t $ha^{-1}$ when 4.5 t $ha^{-1}$ of bio-slurry was applied. Islam (2009) observed an increase in maize growth (plant height, stem diameter and leaf area) when bio-slurry was applied at 70 kg N $ha^{-1}$, which is equivalent to 5 t $ha^{-1}$ of bio-slurry. Hence, to attain meaningful yields under dryland cropping systems, it is recommended that bio-slurry is applied at a rate of 5 t $ha^{-1}$ (Warnars and Oppenoorth, 2014).

Rahman et al. (2008) carried out an experiment to evaluate the effect of different application rates of bio-slurry on plant height, leaf area, number of leaves and the dry matter accumulation of forage maize. The treatments that were used included four levels of bio-slurry $T_0$ (0 t ha$^{-1}$) as a control treatment with no bio-slurry applied, $T_1$ (10 t ha$^{-1}$), $T_2$ (12 t ha$^{-1}$) and $T_3$ (15 t. ha$^{-1}$). From the experiment, significant differences were observed in leaf area among the treatment groups at ($P < 0.05$), as well as height and diameter ($P < 0.01$), which were influenced by the increasing rate of cattle manure at 15, 30, 45 and 56 days after planting. The highest increment in terms of biomass ($p < 0.01$) on maize fodder was observed on $T_2$ (44 t ha$^{-1}$). The authors concluded that an amount of 12 t ha$^{-1}$ is an optimal rate for the biomass production and nutritional value of corn feed.

**Effect of bio-slurry on soil organic carbon and microbial biomass carbon**

Soil organic matter improves the aggregate stability of the soil, faunal activity, resistance to rainfall impact, soil nutrient storage, nutrient availability and rate of infiltration (Brady and Weil, 2008). However, in order to optimise the resource base of the soil and its services, it is essential to manage organic inputs, as well as mineral inputs and soil organic carbon pools. Soil organic carbon can play an essential role, and its sustenance is an effective mechanism to ameliorate land degradation and increase food production. It is used to estimate the amount of soil organic matter or its organic carbon constituents, and a higher content is generally equated to higher fertilizer use efficiency. In addition, it is an index of sustainable land management (Woomer et al., 1994; Nandwa, 2001) and is essential in detecting response to nitrogen and phosphorus fertilization.

About 1 to 3% of total soil organic carbon is comprised of soil microbial biomass, which is recognised as the energetic force for the mineralisation of organic residues in soils (Abaye and Brookes, 2006). Minimum bactericidal concentration (MBC) is considered to be a good index for quantifying soil biological processes as it responds quickly and sensitively to changes in agricultural management. As such, any shifts in soil microbial parameters may be indicative of changes in soil quality from the application of bio-slurry before any alterations can be detected in chemical properties such as nitrogen, phosphorus and carbon content (Odlare et al, 2008). However, a limited number of studies have extensively evaluated bio-slurry decomposition in soils and the related effects on soil carbon turnover, as well as MBC, as for other organic fertilizers, especially from a South African context.

Anaerobic digestion converts organic matter into $CH_4$ and $CO_2$, which escapes the on-farm carbon cycle. Hence, researchers and farmers are anxious that the application of bio-slurry might impair the soil organic carbon status in soils in the long run, compared to undigested manure (Løes et al., 2010; Johansen et al., 2013). For example, high concentrations of readily available nitrogen in the form of $NH_4$ may enhance carbon mineralisation (priming effect) (Senbayram et al., 2009). However, De Neve et al. (2003) reported that organic carbon that is contained in the bio-slurry is more stable when compared to other organic sources.

In an investigation carried out on African soils by Smith et al. (2014), it was reported that, with anaerobic digestion, the amount of carbon sequestered in the soil would be enhanced, creating more stabilised organic matter fractions when compared to composting. However, De la Fuente et al. (2013) reported no significant difference in soil carbon sequestration between bio-slurry and digestate. However, they stressed that further composting of the bio-slurry would help considerably in retaining organic matter in the soil.

The improvement in soil quality results from the application of organic fertilizers due to significant deviations in the structure and diversity of soil microbial communities. Generally, when bio-slurry is applied, soil microbial biomass and metabolic activities are stimulated, which may be attributed to increased carbon and nutrient availability (Odlare et al., 2008; Frac et al., 2012). Similarly, in a study conducted by Makadi et al. (2012), it was reported that the application of bio-slurry did not result in any immediate changes in the soil microbial properties, which included dehydrogenase, catalase, invertase and a number of different groups of soil micro-organisms by plate dilution technique.

However, toxicity from certain trace contaminants, such as chlorinated paraffin, phenolic compounds and polycyclic aromatic compounds (Elfstrand et al., 2007), were identified to have a negative effect on the microbial mediated decomposition of bio-slurry in soils.

The amount of bio-slurry that is applied on agricultural soils may contain substances that hinder the activity of ammonium-oxidising bacteria (AOB) (Nyberg et al., 2004). However, the addition of ammonium stimulates a more rapid response to bacterial and archaeal nitrifiers, as well as denitrifying and $N_2$-fixing populations (Di et al., 2010; Long et al., 2013). As such, evidence indicates that when bio-slurry relative to manure is applied, the archaeal community in the soil is enhanced (Johansen et al., 2013; Abubaker et al., 2013). Walsh et al. (2012) carried out a study to compare the effect of bio-slurry, mineral fertilizer and manure on microbial activity. The study revealed an increase in microbial activity on the soils treated with bio-slurry compared to manure or mineral fertilizer.

The suitability, efficiency and application of bio-slurry as an organic fertilizer in a crop-livestock production system has still not been evaluated under local conditions.

## 2.5 CONSERVATION OF RANGELANDS

### 2.5.1 Water use efficiency of pastures

Various factors affect water use efficiency in pastures. These are soil nutrient status, soil moisture content, soil type and soil management practices.

**Soil nutrient status**

Water availability, water use and nutrient supply to plants are closely related factors that influence plant growth and yield production. Several studies have shown that crops or plants that grow in fertile soils have enhanced WUE. High soil nutrient levels result in increased evapotranspiration (ET) and WUE. Water use efficiency increases with an increase in water supply up to a certain point. Water supply also increases fertilizer use efficiency by increasing the availability of applied nutrients. In fact, water and nutrients exhibit interactions regarding yield (Steduto et al., 2007). Gajri et al. (1993) reported enhancement in water use following nitrogen application. Similarly, optimal phosphorus levels in the soil result in increased root density, depth and the amount of water available to plants. Optimum nitrogen availability in the soil increases water use by plants and reduced evaporation from the soil surface so that total ET was little changed, thereby increasing yields and RUE (Turner, 2004). Phosphorus availability in a balanced soil fertility programme also increases WUE and helps crops achieve optimal performance under limited moisture conditions (Payne et al., 2008; Wang et al., 2011). Nitrogen can affect cold and drought tolerance, yet there is no clear agreement on the extent of its effect. Soil nutrient availability induces large changes in plants' functional attributes, which also affects the water and carbon economy of plants (Mohamed and Ashok, 2014)

**Soil moisture content**

Severe drought stress during the vegetative growth stage and moderate drought stress during the flowering stage of grain sorghum crops contributed to about a 30% reduction in grain yield, despite high WUE (Wang et al., 2011). Prolonged drought may result in the mortality of perennial plants and the switch to annual-dominated flora. High temperature and water deficit reduces net photosynthesis during the period of the constraint, resulting in reduced plant growth rate. Final seed number and seed weight are dependent on the plant growth rate during the flowering period and the seed-filling period, respectively. Consequently, high temperature and water deficit indirectly affect seed number and seed weight. Additionally, severe heat stress may cause the abortion of flowers, causing an indirect reduction in seed number. In the case of forage legumes, $N_2$ fixation is highly sensitive to environmental stress, especially to temperature, water, salinity, acidity and nutrient disorders. Therefore, climate change may affect symbiotic fixation, either directly by impairing *Rhizobia* survival, *Rhizobia* competitiveness, nodule formation, growth or activity, or indirectly by altering carbon supply to the nodules (Vadez et al., 2012).

**Soil type**

Edaphic factors are a major impairment to WUE. The combination of the relative proportion of sand, silt and clay, known as soil texture, has a direct role on the water-holding capacity of the soil. Soil structure is also a crucial factor that affects WUE. Water shortages are prevalent on shallow or course-textured soils. Physical soil constraints like compacted subsoils can be improved by applying gypsum to loosen the soil particles and increase water penetration and root growth (Turner, 2004). Soil aggregates have an impact on the ratio of the soil's macro and micro pores. Soil depth represents the effective root zone depth (Singh et al., 2014). Fine-textured soils with a neutral to an alkaline pH are more suitable for growing cool-season grain legumes, while narrow-leafed legumes like lupins are poorly adapted to fine-textured soils (Siddique et al., 2001)

**Soil management practices**

A significant decrease in production as the range condition deteriorates is a function of the WUE and stability of the different species within a plant community. An improvement in rangeland condition results in improved WUE. This is not only as a result of the influence of veld condition on infiltration rates, but also from the more effective use of available water by climax in comparison with pioneer species. Moderate levels of defoliation can further increase the rain use efficiency of *Themeda triandra* swards. For rainwater to be efficiently captured by the soil, the infiltration rate should be equal to the rainfall intensity for the duration of a storm. The use of minimum tillage or conservation tillage, involving sowing the seed with minimum disturbance of the soil surface by the use of narrow tines, results in a reduction in water loss by evaporation from the soil surface (Botha et al., 2014b). The rainfall quantity and intensity, land slope, soil surface characteristics and plant cover determine the severity of the runoff. Of these, only the latter two are subject to control on a monotonous basis, although land slopes can also be modified by building terraces. Previous studies mainly concentrated on the soil's physical characteristics and how to ameliorate the limitations they impose on infiltration, directly by surface sealing (or crusting) or indirectly by slow subsurface percolation. Surface crusting and restricted infiltration are widespread problems in arid areas and have the potential to limit tillage opportunities in the case of planted pastures. Technologies that affect the physical characteristics of the soil to enhance water availability mainly comprise tillage and anti-erosion measures (Van Duivenbooden et al., 2000).

### 2.5.2 Increasing water use efficiency

Various techniques can be used to increase water use efficiency. These include intercropping and rainwater harvesting.

**Intercropping**

Intercropping systems are generally recommended for rainfed agriculture to realise stable yields. WUE is higher in intercropping system in comparison to sole cropping. Good agronomic practices, such as intercropping, not only improve the utilisation of water, but are an eco-friendly tool for the sustainable management of plant diseases under changing climate (Singh et al., 2014). The inclusion of legumes, such as lucerne, in pasture systems is also known to improve WUE due to their deep tap root system, which allows them to access stored water that is unavailable to shallower rooted grasses. However, it is crucial to note that deeper roots are not always of benefit. In environments where seasonal rainfall and soil characteristics are such that the depth of soil wetting is restricted, deeper rooting will be of no benefit (Turner, 2004). Pastures that fix nitrogen, like lucerne, can also produce double the yield of nitrogen-deficient pastures that utilise the same amount of water (Beef and Lamb, 2014).

Although greater efficiency of resource utilisation is expected from intercropping and mixed cropping in a wide range of environments, it is important to note that this generalisation does not necessarily hold true when the environments are extreme.

In cases where rainfall is infrequent, evaporative losses from the usually dry soil surface may be relatively unimportant. In cases where radiation is limiting, intercrops grown under a cereal canopy that are supposed to utilise a low intensity may, in fact, compete heavily with the cereal for the limited available water. This has been proved to be true in results of a study conducted in Botswana, where intercropped cowpeas had the same effect as weeds in dry years. Even at very low plant density, cowpeas were able to devastate the adjacent rows of sorghum (Van Duivenbooden et al., 2000).

**Rainwater harvesting**

Rainwater harvesting will not only conserve the soil, its fertility and vegetation, but could also be utilised as supplementary irrigation that will be of advantage in enhancing total water supply. The major problem of water management is faced at the time of the seeding of the crop. The ability to conserve residual rainwater and carry it over for the sowing of a particular crop or plant can ensure the timely germination of a crop, as later rains are enough to take care of the crop. Management techniques that increase infiltration and soil water storage, and reduce water losses by runoff, evaporation from the soil surface and evapotranspiration by weeds, result in an increase in the water retained in the soil for subsequent use by crops, as considered in RWH (Singh et al., 2014).

## 2.6 RANGELAND WATER USE

In arid and semi-arid regions, natural rangelands comprise mostly uncultivated landscapes (Palmer and Bennett, 2013), which occur in two different types of land tenure systems: communal and commercial systems (Scogings et al., 1999). This study focuses on communal rangelands: areas of rangeland that belong to the entire community, and to which each member has equal access. In South Africa, communal rangelands mainly occur in the former homelands, such as Ciskei, Transkei, KwaZulu-Natal and Venda, which constitute 13% of the land and support a quarter (25%) of the country's human population (Scogings et al., 1999) through a wide range of goods and services (Palmer and Bennett, 2013). One of these services is providing feed for livestock production, which occurs under an extensively managed system, together with several other natural resources that are harvested for rural livelihoods (Reid et al., 2008).

Apart from supporting the livelihoods of communal people and natural resources such as water, rangelands support livestock production. However, due to degradation, there has been a decline in their ability to use water efficiently (Palmer and Bennett, 2013), with increased water loss through runoff. Palmer and Bennett (2013) also noted that the ability of a rangeland to use water is predominantly driven by the vegetation standing biomass of the rangeland. Where rangelands are communally managed, high stocking rates are prevalent, which leads to low standing biomass. This leads to a rangeland being unable to optimally control and use available water, thus resulting in high runoff water yields and soil erosion. When the standing biomass is low, water runs off from the landscape, and cannot be used to drive evapotranspiration or rangeland production. The process of soil erosion and the inability of the rangeland to optimally use water for rangeland production leads to rangelands being degraded.

The estimates of land degradation vary, largely because of the global increase in human population and industrial activities (Eswaran et al., 2001). The extent of land managed in communal systems amounts to 66% of the global land surface, with 46% of the land surface reported to be slightly to severely degraded. This degradation is estimated to cost USD$40 billion annually (FAO, 2010). About 65% of the land in sub-Saharan Africa is degraded, while 42% is slightly to severely degraded (FAO, 2010).

The impacts of land degradation are mostly found in the dry land areas of sub-Saharan Africa, which have worsened because the ecosystems are susceptible to extreme climate changes (Palmer and Bennett, 2013). The increasing land degradation leads to increased runoff, which cannot be absorbed and used by plants, making it difficult to improve rangeland water use. Thus, the suitable management of water is necessary to restore unproductive, degraded lands.

Land degradation has been redefined beyond the vegetation change and loss of soil to include the reduction in the capacity of land to support society and development, or to perform ecosystem functions and services (Tongway and Ludwig, 1996). Land degradation is considered when the landscape functionally declines to the point where soil nutrients and soil erode (Tongway and Ludwig, 1996). The main drivers are improper, unsustainable land use, and changes in land cover or vegetation and animal species. However, the ineffective management of water and the extent to which land degradation occurs under different land tenure systems and management are still under discussion (Vetter, 2013). Vetter (2013) describes communal rangelands as degraded, based on standing biomass and species composition when compared with commercial properties. These areas look degraded because of continuous grazing and the low standing biomass. Furthermore, compared with commercial farms, which are perceived to be sustainable and an ideal benchmark against other land-use practices, research has been done on the challenges faced by communal farmers. However, there has been no adequate assessment of the level of livestock production and associated products at household level to assess rangeland productivity in communally managed rangelands.

Studies on land degradation conducted in South Africa showed both communal and commercial systems as degraded, but much of the discussion has focused on managed areas (Lloyd et al., 2002). These properties are regarded as the most vulnerable because of the users' inability to collectively and sustainably manage common resources due to a lack of incentives; the so-called "tragedy of the commons" (Hardin, 1968). Furthermore, in South African communal rangelands, degradation can be linked to the inability of land users to respond decisively to environmental indicators that warn of impending state changes, and skew access to resources that accompanied the social engineering prior to 1994 (Beinart, 2000). One can achieve sustainable resource management by linking social and ecological systems. This is possible through the collective action management of common resources. The interest has been on the ecological dynamics of semi-arid rangelands as inherently non-equilibrium systems, which are mainly driven by rainfall and its influence on vegetation dynamics (Vetter, 2005). Although evidence shows that rainfall is a factor in rangeland vegetation dynamics, animal-induced vegetation changes are also evident. The emerging consensus is that differences of equilibrium and non-equilibrium may exist at different spatial and temporal scales in semi-arid rangelands (Vetter, 2005) that are chiefly evident during dry periods. Other edaphic factors, such as increased surface temperatures, elevated $CO_2$, vegetation change and reduced evapotranspiration in the longer term cannot be ignored (Palmer and Bennett, 2013).

The discussions relating to land degradation in South Africa are polarised between commercial livestock production and extensive rangeland management in traditional villages (Vetter, 2013). In the northern part of the Eastern Cape, communal rangelands exist because of the political history, where designated communal rangelands were established during the 20th century by the Natives Land Act of 1913 and the Native Trust Land Act of 1930 (Beinart, 2000). In this area, previously commercial farms are now rangelands that were transferred as a result of the consolidation of the homelands (Beinart et al., 2017). During the dry season, arable lands become a common grazing area where livestock can feed. A long history of communal grazing has been reported, as well as claims associated with land degradation (Beinart, 2003). The Department of Agriculture reported that the rangelands in these areas (that have been part of common property since the 19th century) were degraded as a result of overgrazing and soil erosion (Beinart, 2000; 2003).

In the current political environment, land in the Eastern Cape is being redistributed, and government is committed to improving the livelihoods of previously disadvantaged people in rural areas (Vetter, 2013). Government is looking for a willing seller and a willing buyer for the redistribution of land to the black people living in the former homelands. However, only 5.46% of the land has been distributed to date (Kepe, 2002). The major focus is on the greater land transferee levels and on improved engagement with smallholder agriculture.

A study conducted by Gwate (2018) in the northern part of the Eastern Cape's communal rangelands provided an interesting opportunity to study the dynamics of ecosystem services related to land degradation, rangeland water use and household livestock production. The ability of these rangelands to support primary ecosystem services, such as grazing by livestock and rangeland water use by both livestock and people, is undermined by the land cover changes taking place, such as the invasion of alien plants, the increase in rural settlements, increased afforestation, a reduction in native grassland (Münch et al., 2017) and changes in species composition (Bennett et al., 2012). Thus, it is necessary to better understand rangeland water use and livestock production in order to improve rural livelihoods and optimally manage the landscape.

The concept of water productivity includes the outputs and their associated costs, given the water used by aquatic and terrestrial ecosystems (Molden and Sakthivadivel, 1999). Water productivity is defined as WUE, carbon assimilated and crop yield per unit of transpiration, and later, as the amount of produce per unit of evapotranspiration (Molden and Sakthivadivel, 1999). Irrigation specialists have used other terms, such as WUE, to indicate the amount of water wasted and how effectively it is delivered to the crop. However, the concept does not indicate the outputs produced, or that the water lost through irrigation can be re-used (Seckler et al., 2003). Improving water productivity is most appropriate in water-scarce areas, and reasons for water productivity improvement include meeting the increasing food demand from developing regions in the light of water scarcity (Molden et al., 2007a). Another reason is to respond to pressures in relocating water from agriculture to ensure its availability for environmental use (Molden et al., 2007b). Lastly, improved water productivity contributes to poverty alleviation and economic growth for poor rural areas, which leads to better nutrition, productive employment and more income. The investment cost of the amount of water to be drawn can be reduced by targeting high water productivity (Seckler et al., 2003).

**Importance of water productivity**

Increased water productivity is primarily important in areas where water is a scarce resource and, in agriculture, plays a significant role in facilitating competition for scarce resources, providing food security, and preventing environmental degradation (Bossio et al., 2010). Using less water to grow more food makes water available for other natural and human uses (Sonder et al., 2003). The water consumed by an animal enables the optimal and efficient conversion of feed, and ensures maximum milk production and growth throughout its lifetime (Peden et al., 2003). However, a scarcity of the water that an animal needs to use for body cooling through metabolic processes and transpiration results in low production and health problems.

The amount of drinking water required depends on various factors, such as dry matter intake, feed composition, feed water content, animal species, the live weight of the animal, the level of production, the climate in which the livestock is managed, and the physiological status of the animal (Sonder et al., 2003). Most of the water consumed by the animal is ingested as drinking water or as a component of the feed (Sonder et al., 2003). The feed may be highly variable in moisture content, ranging from 5% in dry feeds to 90% or more in moist feeds (Sirohi et al., 1997). Water that is absorbed directly from dry feeds may not be as important as the water intake, while that derived from moist feeds can supply large amounts of the necessary water requirements (Blümmel et al., 2009). However, there are more opportunities to increase water productivity in the livestock sector under the combined concept of livestock water productivity (Peden et al., 2009).

## 2.7 LIVESTOCK WATER PRODUCTIVITY

Livestock water productivity is defined as the measure of agricultural outputs (goods and services) derived from livestock against the amount of water consumed in the process of producing these outputs (Hoeve and Van Koppen, 2005; Peden et al., 2009). Peden et al. (2007) introduced the concept to investigate interactions and ways to improve livestock production without environmental and water depletion.

The system receives, contains and loses water through various hydrological processes such as precipitation, evapotranspiration, storage, runoff and recharge. The rates of the movement of water through these processes are affected by degradation and depletion (Descheemaeker et al., 2010a). Generally, the amount of water used in a livestock production system consists of not more than 2% drinking water, and only the water lost during the evapotranspiration of feed production is usually considered in livestock water productivity (Descheemaeker et al., 2010a). However, in sub-Saharan Africa and other arid and semi-arid parts of the world, livestock ranching, in a commercial agricultural enterprise, and feeding are the major components of agricultural water use.

Livestock ranching is a significant livelihood strategy for communal farmers in Africa. In land under communal tenure and traditional ownership, livestock's contribution to livelihoods is mainly through providing different products and services. However, their productivity is generally low (Otte and Chilonda, 2003). This low productivity is most often attributed to the poor quality and low quantity of feed, low-yielding breeds, the prevalence of indigenous breeds, inadequate water resources, the prevalence of disease and high mortality rates (Salem and Smith, 2008). Other challenges faced by African smallholders are limited access to credit, lack of technology transfer, high transaction costs and poor market access (Pica-Ciamarra et al., 2011). However, the increasing global demand for livestock products, along with increasing global water competition, population growth and changing nutritional habits (Whaley et al., 2003) have encouraged communal livestock farmers to reevaluate their management practices.

**Livestock-water interaction**

Livestock and water interactions are a crucial challenge, as livestock utilises huge amounts of water for feed production and is responsible for environmental degradation due to overgrazing (Descheemaeker et al., 2011). Water used in livestock rearing is either not valued or is undervalued (Mekonnen et al., 2011). Livestock and water managers face the challenge of guaranteeing that livestock rearing minimises water degradation, depletion and the contamination of resources, while at the same time maximising outputs from livestock and other systems. There is a need to improve the understanding of LWP and its influences on water resources (Kebebe et al., 2015) and to fully understand the interaction of livestock water on the livelihoods of communal farmers.

The major factor influencing the development of different livestock production systems is access to water. This is probably the most significant link between people, the environment and livestock (Descheemaeker et al., 2011). Herd composition, livelihood strategies for coping mechanics and livestock distribution are mainly dictated to by the distribution of water resources and land (Descheemaeker et al., 2011). In areas where water scarcity is the major problem, farmers have adapted to this challenge by adopting a nomadic lifestyle. However, in intensified farming systems, where population is increasing, water competition among the different sectors has increased as the farm size has decreased (Molden et al., 2007a). Livestock water interaction differs, depending on animal herd composition, production objectives, market links, management systems, livestock health and productivity (Peden et al., 2009). In areas where an output, such as draught power, is important, oxen are usually given the priority of a high quantity of quality feed, since they are the major users of water and feed, and have important outputs (Bekele et al., 2017).

Livestock drinking and servicing water such as water used in milking and washing the sheds is the most obvious use of water in a livestock production system, but it is only a small proportion of the total water consumption (Peden et al., 2007).

Studies (Peden et al., 2007; Gebreselassie et al., 2009; Descheemaeker et al., 2009) show that the main use of water in a livestock system is related to the transpiration of water for feed production, which is about 50 to 100 times the amount of water needed for livestock drinking, making it understandable that large quantities of water are necessary to produce a kilogram of meat or a litre of milk.

A study conducted in India by Chapagain and Hoekstra (2003) estimated that 1.96 to 4.6 $m^3$ of water is depleted mainly to irrigate the feed necessary to produce one litre of milk, while estimates of the amount of water required to produce one kilogram of beef are in the region of 10.0 to 12.2 $m^3$. However, the estimates apply only to intensive livestock production, and these estimates do not consider small ruminants, which have a more water-efficient metabolism than large ruminants and equines.

Consideration of the influences of keeping livestock on water resources at the landscape scale is essential when evaluating livestock water interactions because, if the influences are ignored, low LWP could be the result (Peden et al., 2009). Livestock grazing affects the hydrological response of rangelands and results in soil and vegetation degradation. According to a study conducted by Descheemaeker et al. (2006), high grazing pressure leads to a combination of interrelated factors such as poor organic soil matter, poor vegetation cover, soil compaction, poor soil structure, increased soil erosion and higher runoffs from low infiltration rates. However, the tendency of attributing all water lost in the rangeland system to livestock might underestimate LWP (Peden et al., 2007). Land degradation can be severe around the watering points because of the grazing pressure on vegetation cover and the animal trampling effect (Descheemaeker et al., 2009), as well as the contamination of watering points due to mismanagement, such as a lack of fencing and faecal excretion inflow, which can make water unusable (Wilson, 2007). According to Peden et al. (2007), livestock water interaction has received insufficient attention, and much focus has been on land degradation due to grazing and livestock water requirements, resulting in a lack of understanding of feed water productivity and feed intake estimates, which have led to variation in LWP. The lack of knowledge of livestock water interactions has obstructed both proper decision making and the development of methods to improve the situation (Peden et al., 2007). Furthermore, this has resulted in lost opportunities to counter low livestock production, smallholder poverty and land degradation.

**Factors affecting livestock water productivity**

The management of water resources needs to improve worldwide, given the increasing population and water scarcity (Gebreselassie et al., 2009). According to Molden et al. (2007b), the need for improved water management is especially true when water resources are allocated to different and competing uses. There must be a formula for effective strategies to achieve more productivity while, at the same time, improving the environment. This situation aggravates the risk of worldwide food security as sufficient water available for food production is a challenge (Gebreselassie et al., 2009). The increasing population depends on agriculture for food, which competes with household, environmental and industrial uses for the limited water supply (Taddese, 2003). Although all users increasingly demand water, ground water is slowly decreasing, other water ecosystems are degraded and polluted, and the development of new water resources is costly (Descheemaeker et al., 2009). A wide range of pollutants, such as human, agricultural and industrial waste, has contributed to the shrinking of quality freshwater resources (Bennett, 2003).

**Strategies to improve livestock water productivity**

Producing animal feed resources that would consume water more efficiently, as well as selecting livestock species and breeds that have higher feed conversion rates, could improve LWP (Sonder et al., 2003) to sustain the agro-ecosystem (Nardone et al., 2010). Improved grazing of livestock and water management could enhance the productive ability of the land through improved water and soil conservation, which has a potential to reduce pollution such as that of water, and has positive environmental influences. At the household level, LWP can be quantified, which requires developing a methodology to improve the quality of rangelands. Peden et al. (2007) identified numerous strategies to improve LWP.

**Sourcing of feed and management**

The primary strategy for improving LWP is managing and sourcing feed (Haileslassie et al., 2009). The chief water cost in livestock ranching is the photosynthetic production of feed (Sisito et al., 2012). Selecting quality pastures that have high crop water productivity such as feed crops, crop residues and crop by-products helps increase LWP (Ganskopp and Bohnert, 2009). Livestock water productivity is increased by any measure that increases crop water productivity. However, the possibilities for reducing the water consumed in producing feed are limited in number and the results are highly inconsistent (Peden et al., 2003). In practice, maximum feed water productivity is often less than 0.5 kg $m^{-3}$, but can reach 8 kg $m^{-3}$ in rainfed dry matter (Peden et al., 2007). Many factors, such as different concepts of water accounting and the reality of particular production methods, lead to variability (Alemayehu et al., 2012). The important feed choice for improved LWP is the consumption of crop residues and by-products (Burke et al., 2009). Taking advantage of crops grown for human food and the residues of such crops imposes a lower or no additional water cost beyond what the crop itself needs. Low LWP can be achieved by using irrigation water to produce forage, which uses high water cost (Descheemaeker et al., 2010a). Importing feed successfully transfers the water cost of feed production to faraway areas, thus decreasing local agricultural water demand. If the water is not enough to producie feed, animals must migrate to other feed sources or rely on imported feed associated with virtual water, which is the hidden water flow (Chapagain and Hoekstra, 2003).

**Enhancing animal productivity and herd size management**

Higher LWP is mainly possible when one's livestock herds are productive, stress-free and are kept healthy (Haileslassie et al., 2009). When the animals are in a poor condition, production is reduced to zero benefits. A fixed input for livestock production is the water required to produce maintenance feed (Descheemaeker et al., 2010a). Livestock requires additional water to gain weight, work, reproduce and produce milk (Molden et al., 2007a). Energy used for maintenance is less than that required to enhance LWP. However, genetics, nutrition, health, marketing and animal husbandry interventions help improve LWP (Peden et al., 2007). The interventions that help improve LWP include providing quality drinking water (Gebreselassie et al., 2009), selecting breeding stock with improved feed conversion efficiency (Archer et al., 1999), reducing mortality and morbidity through health services (Descheemaeker et al., 2011) and keeping a few, but highly productive animals.

There are two approaches to increasing LWP. The first approach is keeping larger herds that require more feed, water and other inputs with no additional water, which is one way that livestock keepers respond to increased LWP (Amede et al., 2009). The other approach is to keep a few livestock that are highly productive. Some limits are ultimately needed for livestock production, such as restricting land use by animals to certain environmental sustainability levels (Keller and Seckler, 2004), which may include the environmental charge of livestock production in the prices of animal goods and services (Cook et al., 2009). Another limit would be to adopt a policy that ensures reasonable access to animal outputs, such as the use of milk and meat to levels that improve nutrition, and reduce obesity and diabetes (Ebanyat et al., 2010).

**Conserving water resources**

Conserving water resources is the process of limiting water loss through non-production depletion pathways. Natural sustainability, agro-ecosystems and agricultural production depend on transpiration (Peden et al., 2009). Evaporated water and discharge do not contribute to the production of plant material. One of the effective ways to increase LWP is to manage vegetation, land and water through converting evaporation (Peden et al., 2007) and water loss through elevated runoff during storm flow events. Livestock water productivity can be improved by maintaining high vegetative ground cover, harvesting water, improving soil water-holding capacity, developing vegetated buffer zones around water surface bodies, and related measures that decrease extreme runoff and increase infiltration (Descheemaeker et al., 2013).

Livestock grazing has an impact on water, and animals must be managed in ways that maintain vegetation cover. When the vegetation cover is lost, soil erosion increases and infiltration and production in pastures decline (Peden et al., 2003). Moderate grazing pressure has less of a negative impact on water, and on the type and density of grazing on the species composition of the vegetation (Sonder et al., 2003), while high grazing pressure results in the loss of nutritious palatable species. In other parts of the world, very low grazing pressure stimulates bush encroachment (Dalle et al., 2006), but this is not always the case in South Africa, as the interaction between low grazing pressure and the resultant increase in fires inhibits woody encroachment. The combination of reduced grazing and the prevention of fires does, however, result in an increase in woody biomass. High water productivity can be maintained by having more palatable vegetation and animals that utilise the vegetation effectively.

**Allocation of livestock feed and drinking water**

How livestock feed and drinking water is allocated across the landscape can lead to unreasonably low LWP and to land and water degradation. In areas that are near drinking water sources, LWP for cattle is very low because of the morbidity and mortality associated with weight loss and the high risk of disease transmission. Animal production and water productivity is also low when the animals have to walk long distances from feed to watering sites. However, moving water sources creates feed shortages and mortalities.

In arid and semi-arid rangelands, livestock such as cattle, in particular, depends on water resources. When there is limited or no water available, they die and, even if they live, the stress caused by the non-availability of water reduces animal production (Blümmel et al., 2014). The animal drinking process takes place within the system and the water drunk within the process is not depleted, but supports ecosystem functioning (Peden et al., 2006). Water consumed by the animal and lost through urine and faecal moisture can be deposited on the soil, which it may infiltrate or from which it may evaporate (Taddese, 2003). Small amounts of water may also be lost from the pulmonary tissues of the animal as evaporation. Drinking water for animals must be available in small, yet adequate quantities and be of good quality (Wilson, 2007). Although providing a unit of drinking water is costly, the amount of water consumed by livestock is only 2% of that needed to produce feed (Peden et al., 2007).

The amount of water consumed by an animal varies from 20 to 50 ℓ per tropical livestock unit per day, and the consumption depends on factors such as breed, species, temperature, quality of water, feed intake, feed water content, animal activity, pregnancy and lactation (Peden et al., 2003), with high-producing, lactating cows consuming as much as 85 ℓ of water per day. Livestock water productivity, weight gain and milk production can be constrained by water deprivation, which also reduces feed intake (Gebreselassie et al., 2009). In areas where poor water and livestock management is practised, watering sites are often contaminated with sediments, and pastures are overgrazed, contaminating domestic water use that then puts human and animal health at risk (Gebreselassie et al., 2009). Providing water in grazing land is an important contribution and provides an opportunity to distribute livestock for effective forage consumption without overgrazing (Peden et al., 2006).

**Biophysical attributes of the communal rangelands**

Livestock production in semi-arid rangelands can be affected by biotic and abiotic factors, such as stocking rate and rainfall (Fynn and O'Connor, 2000). The concept of Clemensian succession and the theoretical underpinning of range management on ecosystem functioning have been challenged for arid and semi-arid rangelands where a potential determinant of change within a system is rainfall (Fynn and O'Connor, 2000). Stocking rate has traditionally been used as a tool by which range managers can adjust the succession trend of vegetation. However, the current argument is that grazing has a limited influence on the vegetation dynamics because of inter-annual rainfall variability (Fynn and O'Connor, 2000). However, the relationship between livestock and rangeland productivity is positively correlated with mean annual rainfall (Fritz and Duncan, 1994).

On the other hand, grazing has a minimal impact on vegetation in semi-arid rangelands (Baily et al., 1998). Variable rainfall can have a strong influence on rangeland productivity and species composition, although a slight grazing effect on species composition over time can result in a shrinking effect on rangeland productivity (Milchunas and Lauenroth, 1993).

**Livestock production in communal rangelands**

Livestock in communal rangelands provides multiple benefits to its owners: animals are a source of wealth, they provide offtake, hides, wool, milk, draught power and manure. Livestock also provides social prestige, local exchange, bride-wealth payment, loans and accumulation through reproduction (Cousins, 1999; Dovie et al., 2006). However, a decline in the use of livestock draught power and an increase in livestock slaughter remain a central social practice for many communal people (Brown et al., 2013). Currently, livestock production in communal rangelands is not perceived as a thing of the past, but is perceived as having economic potential to address household food security. It is important to state that rangelands exist on a continuum form and may exhibit different dynamics over different spatial scales, such as rangelands that ostensibly appear to be over the larger scale, which may also contain key resource areas where dynamics are more in equilibrium because there is much tighter coupling between plants and livestock.

About 84% of the communal land in South Africa has the potential for livestock production, but livestock sales were thought to contribute little to the cash economy in terms of sales for slaughter in abattoirs (Bembridge, 1987). Because of poor management and low nutrition, the efficiency of communal livestock production in terms of offtake, milk, manure, traction and wool/hides is estimated to be only a quarter of that of commercial rangelands (Bembridge and Tapson, 1993). Factors such as topography, climate and geology can limit crop production and, as a result, most parts of the rangelands are used for livestock grazing, commercial livestock production and game farming (De Wet and Van Averbeke, 1995). Nowers et al. (2013) argue that the deterioration of communal rangelands and low livestock productivity is due to the accelerated degradation of the resource base, but environmental factors such as drought have a greater effect on livestock production. While genetic improvement and improved management can boost livestock production to a certain level, environmental factors cannot be controlled. In the case of commercial livestock production, production is improved by management factors such as vaccination and tick control; in communal livestock production, this is mostly carried out by the government (Nowers et al., 2013). In communal areas, the adoption of technological solutions to the challenges of improving livestock health and productivity has generally been slow for a number of reasons: the high costs of these interventions, inadequate access to extension services and advice, and reliance on non-efficacious traditional veterinary solutions. The provision of veterinary services in South Africa has been significantly reduced (Brown et al., 2013), leaving livestock owners to their own devices, to a large extent, some of whom use plant-based remedies as one of their animal disease management practices (Brown et al., 2013).

Although livestock production in communal areas has low formal offtake rates to abattoirs, and poor economic returns, it is an important source of income. In most communal areas of southern Africa, low-input livestock husbandry remains a primary land-use option (Shackleton et al., 2000). This happens in situations of inconsistent macro-economic policy, changing environmental regimes and labour market policies, where people adopt different livelihood strategies (Cousins, 1999), such as harvesting natural resources and livestock production. In communal economies, livestock herds are regularly multipurpose in character, and when all functions are valued, they produce high rates of economic return per hectare (Dovie et al., 2006). The important functions depend on a number of factors, such as selling livestock for cash, and may be more important in areas that are arid or semi-arid, where the rainfall is erratic (e.g. have a high inter-annual coefficient of variation) and the risk of crop failure is very high (Dovie et al., 2002).

The class identity of the owner also influences the function of livestock and can be highly skewed, due to high levels of crop production and other non-rural sources of income (Cousins, 1996). An individual who owns a relatively large number of cattle normally gives some of the livestock to their kin unconditionally. This may start with the gift of a chicken to a youngster, to a cow when the young man gets married in order to start his own household (Ainslie et al., 2002). The people who benefit most from kinship are usually the men (sons, nephews and brothers), although, in some cases, women benefit too (Bennett et al., 2013). One can motivate to be given livestock by looking after it while one is young, for instance, where an older brother has inherited livestock from his parents, he may give some to his younger brother as a gift (Cousins, 1996). However, in some cases, it is rare for people to gain title to livestock through kinship, unless other customs and institutions contribute to such entitlement (Bennett et al., 2010). Livestock also plays a role between households such as bride-wealth payment, and cooperative arrangements for ploughing and lending, but these roles differ from area to area (Ainslie et al-., 2002).

## 2.8 GRAZING PATTERNS AND MANURE COLLECTION AND STORAGE

Proper livestock grazing distribution is an integral part of rangeland management (Gillen et al., 1984). Managing livestock grazing distribution aims at maximising forage use within a wide range of landscapes without causing serious damage to the land (Gillen et al., 1984). A complex combination of plant community, topographic water distribution, succession stage, time since last fire, aspect, geology and soil, as well as other habitat factors determine grazing distribution. Areas of gently sloping drainage may receive up to 95% of grazing, while steep slopes receive less grazing (Fuhlendorf and Engle, 2001). A better understanding of the livestock interaction with the natural habitat and of management factors should aim at more effective methods of livestock grazing distribution.

Grazing livestock reacts to its environment through behavioural actions that result in different distributions over the landscape (Stuth, 1991). Livestock normally grazes selectively under continuous grazing in search of local areas that lack the accumulation of biomass (Fuhlendorf and Engle, 2001). This behaviour results in small, heavily grazed patches within grazed or ungrazed patches (Bailey et al., 1998). Livestock tends to concentrate its grazing near watering points and along the meadows immediately adjacent to drainage lines, thus leading to increased grazing pressure on areas near watering points and reduced grazing in areas far from watering points (Fuhlendorf and Engle, 2001). This grazing pattern of livestock associated with distance to watering points masks small-scale heterogeneity, leading to rangeland deterioration and resulting in increased runoff (Fuls, 1992).

To maximise livestock distribution across the landscape, grazing systems such as rotational grazing are designed to harvest forage uniformly. Livestock managers believe that rotational grazing can improve the rangeland condition and livestock production more than continuous grazing where livestock is allowed to range freely and select grazing according to their own preferences. However, studies demonstrate that continuous grazing at light intensity does not degrade species composition and rangeland production (Holecheck et al., 1998). Unlike most commercial rangelands where livestock is rapidly rotated across the landscape through relatively small pastures, communal rangelands allow livestock to graze freely and continuously across the landscape with or without the presence of a herder.

Herding is the activity of keeping animals together as a group while searching for forage to graze or water to drink. Herding involves keeping and guiding the animals to prevent them from wandering, fighting or being subject to predators. Samuels et al. (2013) argue that herd mobility is an adaptable, efficient way to manage livestock in communal rangelands as it responds to environmental and socio-economic variables. On the other hand, livestock grazing in fenced paddocks has limited access to key resources and so the practice breaks down during dry seasons. In South Africa, the long history of colonialism led to the reduction of land available to Africans and significant restrictions on livestock movement. In communal areas, livestock was kept in kraals at night and released in the morning with a herder to move it around the rangeland. However, mandatory schooling meant a decrease in the number of households practising the traditional herding of livestock, which had been drawn mainly from child labour.

On the other hand, it is unclear why currently under-employed men in rural villages are not considered suitable for herding animals. In the Eastern Cape, smallholder farmers can seldom afford to pay for a herder to move their livestock across the landscape. In a rotational grazing management system, the livestock owner aims at uniform utilisation of the rangeland in order to achieve more livestock production. However, in circumstances where livestock is forced to ingest low-quality herbage, this may decrease livestock production and sustainability. Furthermore, in the context of the Eastern Cape, the colonial betterment programmes created grazing paddocks on community rangelands that were inappropriate for managing the large numbers of livestock within the system, particularly during the dry season. The widespread removal of fences in the post-apartheid era enabled livestock to forage over larger distances and gain access to key resources, giving them a better chance of survival, particularly during the dry season.

## 2.9 BIOGAS AS A RENEWABLE ENERGY SOURCE

### 2.9.1 Introduction

Over 90% of power generation in South Africa is from coal-fired power plants, whereas renewable energy power sources are producing less than 6% of the total energy. South Africa is a country with abundant, diverse and unexploited energy resources that are yet to be used for improving the livelihood of the vast majority of the population. The South African Integrated Resource Plan (IRP), approved by Parliament in 2010, sets a target of 40% renewable energy contribution by 2030 (Department of Energy, 2010).

Biogas technology is based on the anaerobic digestion of bio-wastes such as agricultural waste, and municipal and industrial waste, and is a promising technology, which can ease energy shortage and environmental problems in South Africa. Biogas production would benefit mainly the rural population by providing clean fuel and reducing energy poverty. According to AGAMA Energy (2003), household biogas digesters have the potential to reach 400,000 residences in South Africa, and 50,000 could be installed by 2020.

Most rural areas in South Africa are sparsely populated and far from the electricity utility grid, therefore making it expensive for the utility company (Eskom) to connect electricity to scattered rural houses (Mapako, 1997). The unavailability of grid electricity leaves rural communities with few options, one of which is the installation of biogas digesters. Biogas is a frequently overlooked source of fuel, despite the excitement surrounding the use of bio-fuels as an alternative source of energy. The use of biogas digesters could improve the lives of the people in rural areas in many ways; it reduces deforestation, reduces greenhouse gas emissions and controls unpleasant odours from human or animal waste, and reduces the workload, mainly of women, in firewood collection. Biogas is a colourless, flammable gas produced via the anaerobic digestion of animal, plant, human, industrial and municipal waste, among others, to give mainly methane (50–70%), carbon dioxide (20–40%) and traces of other gases such as nitrogen, hydrogen, ammonia, hydrogen sulphide and water vapour. It is smokeless, hygienic and more convenient to use than other solid fuels. Biogas is a by-product of waste treatment in animal farms and can be used to replace fossil fuel to produce electrical energy. Biogas is formed by the digestion of animal waste by anaerobic bacteria. The approximate composition is 60–80% methane, 20–40% carbon dioxide and about 1% hydrogen sulphide and other trace gases. Biogas has a liquefying pressure of 200–300 bar and a heating value of about 23,400 kJ $m^{-3}$. The gas density is 1.2 kg $m^{-3}$ and has a research octane number of about 130. From the above properties, it can be seen that it is difficult to liquefy biogas for storage or transport, but it is quite suitable for use as fuel in an internal combustion engine (Siripornakarachai and Sucharitakul, 2007).

Biogas results from the microbial degradation of biomass, formed through photosynthesis by solar power in accordance with Equation 1.

$$6CO_2 + 6H_2O + Es \rightarrow C_6H_{12}O_6 + 6O_2 \quad (1)$$

Biogas can be viewed as one of the vehicles to reduce rural poverty, and leads to rural development. Anaerobic digestion produces less greenhouse gases than waste treatment processes such as composting (Walker et al., 2009) and land filling (Lou and Nair, 2009). The technology is appropriate for the recovery of energy as it provides renewable energy and fertilizer. The methane from biogas is a source of renewable energy that produces electricity in combined heat and power plants (Clemens et al., 2006). The biogas can even be used to complement coal in grid electricity.

Biogas technology involves the use of digesters, which are vessels in which animal waste and other biodegradable organic material are broken down into methane and traces of carbon dioxide and hydrocarbons. Biogas digesters are excellent waste disposal systems for wastes such as night soil (human wastes), thereby preventing the environmental contamination and spread of pathogenic diseases such as cholera and diarrhoea. The composition of biogas varies depending on the raw materials, the organic load applied, the retention period and temperature. The gas consists mainly of methane, which is generally between 55 and 80%. Biogas is about 20% lighter than air and has an ignition temperature in the range of 650 to 750 °C (Deublein and Steinhauser, 2011).

### 2.9.2 Background to anaerobic digestion

Anaerobic digestion is a biological process that occurs naturally when bacteria decompose the organic matter, producing mainly methane and carbon dioxide in an oxygen-free environment (Arsova, 2010). The anaerobic digestion process is divided into four steps: hydrolysis, fermentation (acidogenesis), anaerobic oxidation (acetogenesis) and methanisation (Davidsson, 2007; Leksell, 2005; Polprasert, 2007).

**Hydrolysis**

Hydrolysis is an enzyme-mediated stage where insoluble organic compounds such as proteins, fats, lipids and carbohydrates are converted into soluble organic components such as amino acids, fatty acids, monosaccharides and other simple organic compounds (Yadvika et al., 2004). The process is represented by Equation 2.

$$(C_6H_{10}O_5)n + nH_2O \rightarrow nC_6H_{12}O_6 \quad (2)$$

The overall hydrolysis rate depends on organic material size, shape, surface area, biomass concentration, enzyme production and adsorption (Parawira et al., 2004; Boe, 2006).

**Acidogenesis or fermentation**

In this step, soluble compounds produced in the first stage are further degraded, resulting in the production of carbon dioxide, hydrogen, organic acids, alcohols and some organic sulphur compounds (Gerardi, 2003). The degradation of monosaccharides, e.g. glucose, can manifest in different pathways, which lead to the emergence of different products. The important acid at this stage is acetic acid as it is the principal organic acid used as a material by methane-forming organisms. At a pH greater than 5, the production of volatile fatty acids is increased, whereas at lower pH levels (less than 5), more ethanol is produced, and at even lower pH levels (less than 4), all processes may cease.

**Acetogenesis**

The third stage of acetic acid formation (acetogenesis) combines the prior acidification with methane formation. The starting substrates are a number of final products from the acidification phase. Examples include chain fatty acids, propionic acid, polymer substrates (carbohydrates, fats and proteins) and butyric acid. Together with lactic acid, alcohols and glycerol, the acetogenic micro-organisms convert these substrates into acetic acid, hydrogen and carbon dioxide (Wiese and Oeynhausen, 2009). This process is presented by Equations 3 to 5.

$$CH_3CH_2COOH + 2H_2O \rightarrow CH_3COOH + CO_2 + 3H_2 \quad (3)$$

$$CH_3CH_2CH_2COOH + 2H_2O \rightarrow 2CH_3COOH + 2H_2 \quad (4)$$

$$2CO_2 + 4H_2 \rightarrow CH_3COOH + 2H_2O \quad (5)$$

**Methanogenesis**

Methanogens convert the acetate and hydrogen to methane and carbon dioxide. Methanogenic bacteria are divided into three categories.

- Hydrogenotrophic methanogens use hydrogen to convert carbon dioxide to methane according to Equation 6.

$$\begin{array}{ccccccc} 4H_2 & + & CO_2 & \rightarrow & CH_4 & + & 2H_2O \\ \text{Hydrogen} & & \text{Carbon dioxide} & & \text{Methane} & & \text{Water} \end{array} \quad (6)$$

- Acetotrophic methanogens split acetate into methane and carbon dioxide.
- Mmethylotrophic methanogens produce methane directly from methyl groups, such as methanol, and mono-, di- and trimethylamines.

The largest contributors to methane production in anaerobic digestion are acetotrophic (acetate splitting) methanogens, which generate approximately 70% of methane produced in digesters. In most digesters, less than 30% of the methane originates from the reduction of carbon dioxide by hydrogenotrophic methanogens, while the remaining 1 to 2% of the methane is produced by methylotrophic methanogens (Gerardi, 2003).

Methanogens have a narrow substrate spectrum and are sensitive to the presence of oxygen (Dhaked et al., 2010). The reaction that takes place in the process of methane production is called methanisation and occurs over various intermediate processes.

### 2.9.3 Factors affecting the rate of digestion

Parameters within an anaerobic digester that play a key role in the physical environment and efficiency of digestion and biogas production potential include pH value, temperature, concentration of solids, hydraulic retention time, redox potential, volatile solids (VS) and loading rate, inocula, carbon-to-nitrogen ratio, toxicity, ammonium, particle size, water content, agitation frequency, organic loading rate and volatile fatty acids.

**The pH value**

The pH value describes whether a substance is chemically acidic, neutral or alkaline. It depends on the amount of free hydroxonium ions per unit volume. Different groups of micro-organisms involved in anaerobic digestion require different pH levels. The optimum pH level for hydrolysis and acidogenesis is between 5.5 and 6.5 (Arshad et al., 2011). The ideal pH for methanogens is between 6.8 and 7.6, and their growth rate is rated below pH 6.6 (Mosey and Fernades, 1989). When the pH is less than 6.1 or greater than 8.3, the biogas yield is decreased (Lay et al., 1997).

**Temperature**

In biogas production, temperature of the slurry is an important parameter that affects the rate of biogas production. In nature, methane is formed over a wide temperature range of 0 to 97 °C (Dhaked et al., 2010).

An increase in ambient temperature generally increases the rate of reaction and therefore the rate of biogas production. All the metabolic processes in bacteria are brought about by enzymes. These microbes have the temperature range within which they can thrive. When the temperature is not favourable, the enzymes may be denatured, hence hampering their digestion process. In this regard, bacteria are classified according to their preferred temperature. Psychrophilic bacteria work best between 10 and 20 °C, mesophilic bacteria between 20 and 35 °C and thermophilic bacteria between 45 and 60 °C (Davidsson, 2007).

**Hydraulic retention time**

The amount of gas produced depends on the volume of slurry in the biogas digester, normally being about two-thirds of the digester volume (Fulford, 2001). The digester volume is also related to the retention time measured in days and the loading rate, in terms of manure fed per unit liquid volume (Thy et al., 2003). The average time spent by the biomass inside a biogas digester before it comes out from the digester is known as hydraulic retention time. The process of degradation of biomass requires at least 10 to 30 days in a mesophilic condition, while in a thermophilic environment, the hydraulic retention time is usually less than ten days (Demetriades, 2008).

**Carbon to nitrogen ratio**

The C:N ratio is a measure of the relative amounts of organic carbon and nitrogen present in the substrate. The C:N ratio of waste is determined by its composition. If the C:N ratio of slurry is very high, the nitrogen will be consumed rapidly by methanogens to meet their protein requirements and will no longer react on the remaining carbon content of the material. Therefore, the waste used as a single substrate will be deficient in nitrogen, which is needed to build up of bacterial communities. As a result, biogas production will be low (Adelekan and Bamgboye, 2009).

A C:N ratio of 20:1 to 30:1 is considered optimal for the anaerobic digester based on the biodegradable organic carbon (Mshandete et al., 2004). Animal waste such as cattle dung has an average C:N ratio of 24:1. To maintain the C:N level of a material at acceptable levels, materials with a high C:N ratio can be mixed with those with a low C:N ratio. The C:N ratios of some commonly used material are presented in Table 2.1:

**Table 2.1: C:N ratio of some organic materials (Kourik, 1986)**

| Raw materials | C:N ratio |
|---|---|
| Human excreta | 8 |
| Chicken manure | 10 |
| Goat manure | 12 |
| Pig manure | 18 |
| Sheep manure | 19 |
| Cow dung | 24 |
| Straw (maize) | 60 |
| Straw (rice) | 70 |

Some of the characteristics of animal waste are as follows:

- **Cattle dung**: It is most commonly used because it is easily formed onto a homogeneous slurry and its C:N ratio is near the optimal value. The composition of cow dung in percentage is:
  Total solids (TS) = 17.63, VS = 13.65, organic carbon (OC) = 44.01 and total nitrogen = 1.37 with a C:N of 32.10 and a pH of 5.

- **Pig manure**: It has a lower C:N ratio than cattle dung (13:1 to 15:1). On account of the low C:N ratio, pig manure is better utilised by mixing it with other materials. Common mixture compositions are: (a) 60% pig manure, 20% night soil and 20% plant matter; (b) 60% pig manure, 25% cow manure and 15% plant matter; and (c) 63% pig manure, 25% cow manure and 12% chicken manure.

- **Poultry manure**: It has a C:N ratio of 15:1 and needs to be mixed with other materials.

- **Night soil**: It has a C:N ratio of 10:1. Night soil prevents problems of corrosion of mild steel and differential settling. The high $H_2S$ content in the slurry affects engines running on biogas unless the gas is purified.

**Water content**

Water is the vital nutrient for micro-organisms' life and their activity. The movement of bacteria and activity of extracellular enzymes are highly determined by the water content in the digester (Nijaguna, 2002). Optimal moisture content has to be maintained in the digester and the water content should be kept in the range of 60 to 95% (Demetriades, 2008). However, the optimal water content differs with different input materials, chemical characteristics and bio-degradation rate (Nijaguna, 2002).

**Agitation/mixing**

The close contact between micro-organisms and the substrate material is important for an efficient digestion process. This can be achieved in a number of ways, e.g. daily feeding of the substrate instead of a long interval provides the desired mixing effect. Agitation is critical to the successful operation of an anaerobic process.

Poor agitation will lead to stratification within the digester and partially digested sludge being withdrawn (Gray, 2004). The installation of certain mixing devices, such as a propeller, scraper or piston, is also a mechanism for stirring (Yadvika et al., 2004). Stirring enhances methane production and significantly reduces the decomposition of solids inside the digesters in thicker manure digestion. Agitation results in higher reaction rates (Cubas et al., 2011). The best agitation frequency varies depending on the intended use of the reactor in question (Kobayashi and Li, 2011).

**Organic loading rate**

The rate at which substrate is supplied to the digester is referred to as the organic loading rate. It is usually expressed in terms of kg VS $m^{-3}$ $day^{-1}$. The gas production rate in the digester is highly dependent on the organic loading rate (Yadvika et al., 2004).

**Volatile fatty acids**

Volatile fatty acid accumulation can lead to a drop in pH, which inhibits the micro-organisms. A continual drop in pH can result in biogas digester failure. Volatile fatty acids are needed in small amounts as part of an intermediary step for the metabolic pathway of methane production by the methanogens (Carucci et al., 2005). This conclusion was supported by El-Mashad and Zhang (2010), who stated that VFA is one of the three primary buffer agents needed to maintain the pH value, and hence the ammonia concentration, within the desired range. The operating parameters of a typical biogas digester are listed in Table 2.2.

**Table 2.2: Operating conditions for anaerobic digestion (Engler et al., 1999)**

| Operating parameter | Typical value |
|---|---|
| Mesophilic temperature | 35 °C |
| Thermophilic temperatures | 54 °C |
| pH value | 7–8 |
| Alkalinity | 2,500 mg $\ell^{-1}$ (minimum) |
| Retention time | 10–30 days |
| Loading rate | 2.4–5.6 kg VS $m^{-3}$ $day^{-1}$ |
| Biogas yield | 0.19–0.5 $m^3$ $kg^{-1}$ VS |

### 2.9.4 Biogas digester types

Four factors determine the optimal design and installation of a digester. The amount and nature of feedstock available on site is the first driving factor. If the installation requires more feedstock every day than is available to the household, the digester will not perform effectively. The energy demand is the second factor determining the size of the digester. There is no value in installing a biogas digester that produces more biogas than the household needs. This would mean wasted time and labour in feeding the digester and the need to vent excess biogas. The cost of the system is a strong determinant. Finally, an issue that is often overlooked is the space available for the installation. If the household is in an urban setting, there may be insufficient space for a permanent underground structure. If the house is rented, the householder may prefer a system that can be moved when the rent expires.

The most common types of biogas digesters are the fixed-dome digester, balloon-type digester and floating drum digester. This project focused on fixed-dome and balloon-type digesters, as discussed below.

**Fixed-dome digester**

The fixed-dome digester is the most popular digester. Its archetype was developed in China as early as 1936. It is a closed dome-shaped digester with an immovable, rigid gasholder and a displacement pit (compensating tank). The biogas produced by methanogenic bacteria in the biogas digester is captured in the gasholder and the slurry is displaced in the compensating tank. When gas is consumed, slurry returns to the digester from the overflow tank. As a result of these movements, a certain degree of mixing is obtained. The more gas that is produced, the higher the level at the slurry outlet (Fulford, 2001).

The fixed-dome digester has some advantages, which include it being relatively cheap and durable, not having any moving parts and being well insulated. However, the fixed-dome digester has disadvantages as well. These include high technical skills being required for a gas-tight construction, a special sealant being required for the gasholder, it being difficult to construct in high water table areas, it requiring more exaction work, as well as enormous structural strength for construction (Nijaguna, 2002, Sharma and Giuseppe, 1991).

**Balloon digester**

A balloon digester (bag digester) is a plastic or rubber bag that combines the gasholder and the digester. This is a plug-flow type reactor. This design was developed in Taiwan in the 1960s. Gas is collected in the upper part and manure in the lower part. The inlet and outlet are attached to the skin of the bag. The pressure of the biogas is adjustable by laying stones on the bag (FAO, 1996). The advantages of bag digesters include low cost, simple technology and being easy to clean. However, the disadvantages include a short lifespan, it being susceptible to physical damage, hard to repair, needing high-quality plastic and being difficult to insulate (APCAEM, 2007).

### 2.9.5 Biogas composition

The biogas consists of different components. The main compounds are methane and carbon dioxide. Gas composition is influenced by the substrates utilised, as shown in Table 2.3. Table 2.4 gives a summary of various aspects related to the feed materials and products of a biogas digester.

**Table 2.3: Specific potential biogas yield and methane content of different organic compounds (Baserga, 1998)**

| Compound | Biogas ($m^3$ $kg^{-1}$ of DM) | $CH_4$ content (percentage) | $CO_2$ content (percentage) |
|---|---|---|---|
| Protein | 0.70 | 71 | 29 |
| Fat | 1.25 | 68 | 32 |
| Carbohydrates | 0.79 | 50 | 50 |

**Table 2.4: Biogas yield on weight basis (Nijaguna, 2002)**

| Raw material | Biogas yield ($m^3$ $kg^{-1}$ of dry matter) |
|---|---|
| Cow dung | 0.34 |
| Poultry manure | 0.46–0.56 |
| Chicken manure | 0.31 |
| Pig manure | 1.02 |
| Sheep manure | 0.37–0.61 |
| Algae | 0.32 |
| Night soil | 0.38 |

From Table 2.4, it can be observed that pig manure has the best biogas output in terms of volume. Cow dung has a lower biogas yield than sheep manure. Table 2.5 shows the general properties of the biogas.

**Table 2.5: General features of biogas (Deublein and Steinhauser, 2011)**

| Parameter | Properties |
|---|---|
| Biogas composition | 55–70% $CH_4$<br>30–45% $CO_2$<br>Traces of other gases |
| Energy content | 6.0–6.5 kWh $m^{-3}$ |
| Fuel equivalent | 0.60–0.65 L oil $m^{-3}$ biogas |
| Ignition temperature | 650–750 °C |
| Critical pressure | (7.5–8.9) × $10^6$ Pa |
| Critical temperature | -82.5 °C |
| Normal density | 1.2 kg $m^{-3}$ |
| Smell | Bad eggs |

#### 2.9.6 Summary

The literature review covered the digestion process, the various biogas digester designs, the use of biogas for cooking in rural areas, as well as the use of bio-slurry as a fertilizer. The factors affecting the choice of the site for the construction of a digester were also reviewed. The review highlighted the current status of rural household digesters. It was established that the industry is at its infancy stage in South Africa. However it is growing quickly. Although there is information about the use of bio-slurry, the available literature does not provide information on the quantities to apply in the soil. A number of challenges were also established with the use of bio-slurry as a fertilizer, although it was generally stated that bio-slurry is a good fertilizer. Therefore, there is need for research to determine the sustainable mixing ratios for bio-slurry as a soil fertilizer.

# CHAPTER 3: SITE SELECTION AND DESCRIPTION OF STUDY AREA

## 3.1 INTRODUCTION

Project team members, consisting of researchers from the ARC-SCW, the Eastern Cape DRDAR, the University of Fort Hare and Fort Cox College, compiled selection criteria, which were used to draw up a list of possible rural villages where the project could be implemented with the assistance of the local extension officers. This was followed by site-specific visits and discussions with village leaders and members. A project team meeting was again arranged to arrive at the final localities selected from the shortlisted villages.

The project intended to upscale RWH&C techniques to croplands and rangelands for food and renewable fuel (biogas) production. Therefore, the selection of the most appropriate study area was a critical factor in the effective implementation of the project. The project had to focus on the following:

- An area where people do not have access to electricity and still depend on other sources for their energy needs
- An area where livestock production (cattle) is the most common practice
- An area where people have the opportunity to harvest rainwater from the roof area in their homesteads
- An area where there is potential for crop production on the croplands in semi-arid areas

The shortlisted villages in the Eastern Cape were the following:

- Hobeni (Mbhashe Municipality, Amathole District)
- Ncihana (Mbhashe Municipality, Amathole District)
- Silindini (Ngcobo Municipality, Chris Hani District)
- Dudumashe (Mnquma Municipality, Amathole District)
- Krwakrwa (Nkonkobe Municipality, Amathole District)

In order to select the best study area for project implementation, the project team visited the shortlisted villages. The aim of these visits was to get a clear picture of the homesteads, rangelands, croplands and soils, and to interact with the villagers. They contacted the local extension officers to schedule meetings with the traditional leaders (chiefs) and villagers of the shortlisted villages, visited the agricultural district managers to introduce the team, and discussed the possible project with the local extension officers. The local extension officers accompanied the project team to the shortlisted villages and facilitated the meetings. The possible project was explained, after which the villagers had an opportunity to ask relevant questions. Afterwards, group interviews and discussions were conducted with the village members from a structured mini-questionnaire, which assisted in evaluating the potential villages in terms of the identified criteria. During the site-specific visits, score sheets were used to rate the shortlisted villages. Evaluation criteria included access to electricity, sources used for lighting, sources used for cooking, number of livestock, annual rainfall, soil properties, the availability of rangelands, the use of croplands, support services and access to water sources. Krwakrwa scored the highest, closely followed by Dudumashe, then – with much lower scores – Hobeni, Silindini and Ncihana. Based on the scores and numerous advantages, it was decided that the project would be implemented in Krwakrwa Village in the Amathole District of the Eastern Cape. Krwakrwa is situated on the road between Alice and Hogsback. Its coordinates are 32°44'431" S and 26°54'338" E. This was subjected to the condition that officials from the DRDAR committed themselves to overseeing and managing the project on a day-to-day basis as the ARC's project team members were stationed too far from the project sites to be there all the time.

After Krwakrwa was selected from the five shortlisted communities that were identified, interactions between the project team and villagers were more intense and focused on explaining the background and aims of the project, as well as the responsibilities of all the parties. This culminated in drawing up a Memorandum of Understanding (MoU) between the various project team members and the villagers. The signing of the MoU paved the way for the project in terms of achieving its aims and objectives. It also improved and opened up the lines of communication between the stakeholders. The MoU formed the legal document outlining the terms and details of the agreement between the parties, including each party's requirements and responsibilities. Villagers from the neighbouring village, Upper Ncera, showed a keen interest in the project that was conducted in Krwakrwa, and it was decided to expand the project to Upper Ncera as well.

After the villages had been selected, a baseline study was conducted to gain a better understanding of the situation in the respective villages. The villages were described in terms of their natural resources (climate, topography, soil, vegetation, types of livestock and their numbers, and the carrying capacity of the rangeland), human resources (socio-economics, current sources of energy and usage, and demographics) and farming systems.

## 3.2 NATURAL RESOURCES

### 3.2.1 Soil

Krwakrwa is situated on the road between Alice and Hogsback in the Tyhume River Valley at the foothills of the Amatole Mountains. There are many good-quality soils in the area, but also areas with shallow top soils (A-horizons), as well as areas with very shallow soils that were never cultivated. Overgrazing has caused major erosion trenches throughout many parts of the village with the A-horizon washed away in many areas. Good planning with the village is very important to optimise the use of the higher-potential soils and to engage in good management practices on the lower-potential soils in order to conserve the soil and protect the area.

The slopes in the Krwakrwa and Upper Ncera villages vary from about 30% to very flat areas. The villages' houses are situated in the middle of the village border, where the area ranges from relatively flat to slopes of around 8%. The main croplands are situated on the eastern side of the village with old croplands situated around the south-western and western borders. The slopes on the croplands range from around 1% to a slope as steep as 30%. The rangelands are situated on the northern and north-western side of the village, as well as on the south-eastern and southern side of the village.

A reconnaissance soil survey was conducted to confirm the soil forms. The most prominent soil forms in the area and soil depth were identified through auguring. Auguring was done at randomly selected homestead gardens, as well as the croplands and rangelands. The soils were classified using the South African Soil Classification System (Soil Classification Working Group, 1991). During site visits, soil samples were also taken for analyses of clay percentage, exchangeable cations, cation exchange capacity, pH, organic carbon and phosphorus.

The parent material in the region consists mainly of grey mudstone, shale and sandstone of the Balfour Formation, Adelaide Subgroup, Ecca Group (Geological Survey, 1974).

It was found during the desktop study that the dominant soil forms in the Krwakrwa area were the Westleigh, Glenrosa and Cartref soil forms. Other soil forms found were Oakleaf, Mispah, Valsrivier, Mayo, Hutton and Bonheim. During the soil survey, it was found that the Hutton form occupied the largest part of the cropland area, followed by the Avalon and We soil forms. The Hutton soil form was mostly found within the villages' active croplands. The Hutton soils were mostly found upslope, grading into Avalon in the lower lying areas. Shortland soils were found on the north-eastern croplands.

The Hutton (Hu) soil form was found to comprise the largest area in the village, as well as a large percentage of the croplands. The soil form occurred mostly on the eastern side of the village on the upper slopes of the croplands. When moving in a westerly direction, the soil became more structured, and ultimately the Shortland soil form became more dominant. The topsoil ranged from dark red to strong brown to a dark yellowish brown, while the subsoil ranged from dark red to a dark reddish brown. The clay content ranged from 5 to 30% in the topsoil and 8 to 40% in the subsoil. Most of the Hu soil forms are on average deeper than 2 m with no limiting material. The Hu on the rangelands tends to be shallower with saprolite as the limiting material. This soil has a high potential for crop production (croplands and homesteads) due to its depth (more than 2 m in most instances) and high clay content. Both these factors are favourable for increasing water storage for increased crop production, as well as improved rangeland production. Farmers are currently ploughing these soils, although they suffer losses due to water stress.

The Avalon (Av) soil form occupies the second-largest part of the villages' croplands, although it is less dominant on the rangelands. The soil was mostly found on the lower-lying areas of the croplands where the Hu soil form graded downslope into the Av soil form. This soil form consists mainly of strong brown, dark yellowish brown topsoil, which overlies dark yellowish brown to yellowish brown subsoil horizons. The orthic A-horizon ranges from 200 to 300 mm with the yellow brown apedal B-horizon averaging around 300 to 500 mm. In many cases, the soil is deep with a soft plinthic B-horizon of around 300 to 600 mm. The clay content in the topsoil ranged from 5 to 15%, while in both B-horizons, it ranged from 15 to 40%. This soil form is quite deep with a maximum depth of 1,200 mm. As in the Hu soil form, the Av soil form is suitable for RWH&C practices due to its depth, as well as its high clay content. The Av form is a good soil for crop production (croplands and homesteads), as well as for rangeland production.

The Westleigh (We) soil form occupies the third-largest part of the village. Many croplands are situated on We units, although it is more dominant on the rangelands and old croplands. The We soil form is more dominant towards the western boundary of the village. This soil form consists mainly of a bleached topsoil, which overlies a dark yellowish brown to yellowish brown soft plinthic B-horizon. The orthic A-horizon ranges from 100 to 300 mm with the soft plinthic B-horizon averaging around 300 to 500 mm. In many cases, the soil is very shallow, with an average depth of 400 to 500 mm. Croplands were found where the average soil depth over 3.5 ha was only 300 mm. This is very dangerous for cultivation, since erosion of the plinthic layer will take place if the topsoil is lost. This was seen in many cases throughout the croplands. The clay content in the topsoil ranged from 5 to 10%, while both B-horizons ranged from 15 to 30%. The We soil form is very poor for crop production unless it has a deep orthic A-horizon. It was stressed that the villagers should not plough the shallow We soil form. At least 10 ha of ploughed fields were identified that had almost no crop production potential. The fields were very shallow (300 to 500 mm) and the soft plinthic B-horizon was ploughed to the soil surface. In some cases, no A-horizon existed. It was therefore recommended that these areas must either be used for planted pastures or be reseeded with perennial grasses.

The Shortland (Sd) soil form occupies the fourth-largest part of the villages' croplands and is just as dominant on the higher-lying rangeland areas. The Sd soil form occurs mainly on the upper slopes of the croplands on the southern side of the village. The structure is very strong where these soils occur. The topsoil ranged from dark red to strong brown, while the subsoil ranged from dark red to a dark reddish-brown. The clay content ranged from 5 to 30% in the topsoil and 8 to 50% in the subsoil. Most of the Sd soil forms were on average deeper than 1.2 m with no limiting material. The high clay content and depth of these soils make it possible to produce crops (croplands and homesteads) using RWH&C techniques. The Sd form is a good soil for crop production (croplands and homesteads), as well as rangeland production.

The Clovelly (Cv) soil form, which is similar to the Av soil form, comprised a fifth of Krwakrwa. The colour of the topsoil was found to be a dark yellowish-brown, while the subsoil was brownish-yellow. The clay content of the topsoil ranged from 5 to 15%, while the clay content of the subsoil ranged from 10 to 20%. The Cv soil forms in the area were found to be very shallow, never deeper than 400 to 500 mm. The Cv soil form occurring in Krwakrwa is generally too shallow for crop production and should rather be used for planted pastures or planted with a perennial grass.

The highest percentage of Oakleaf soil forms were found near the north-western boundary of the village's rangelands, as well as large areas in the homestead gardens. The clay content ranged from 15 to 20% in the topsoil to up to more than 30% in the subsoil. The soil depth ranged from 500 to 1,000 mm deep. In terms of soil colour, the pattern is uniform from topsoil to subsoil except that the topsoil is a little darker than the subsoil. This might be attributed to the organic content of the topsoil. This soil unit has the potential for crop production (croplands and homesteads) in terms of RWH&C specifications. The soil depth was found to be deep enough (1,000 mm in certain areas) and the clay content also fitted the specifications for RWH&C. The Oakleaf form is a good soil for rangeland production.

The Griffen (Gf) and Glencoe (Gc) soil forms both have yellow-brown apedal B-horizons, although the Gf soil form has a redder yellow-brown apedal B-horizon than the Gc soil form. The Gc horizon has a hard plinthic C-horizon, which does not make it suitable for crop production on the croplands, especially if the B-horizon is shallow. The Gc soil form was also found in a few homestead gardens, which were relative shallow. The clay content of the A- and B-horizons were similar for both soils, with the clay content in the A-horizon being between 5 and 15% and the clay content in the B-horizon being between 10 and 20%. In the case of the B2-horizon in the Gf soil, the clay content was the same as the B1-horizon, being between 10 and 20%. The B2-horizon was very granular with a high coarse sand fraction. The depth of the soils vary from around 500 to 1,200 mm. The shallow Gc soil form found on the croplands is not suitable for crop production due to its hard plinthic limiting layer. Where the Gc soil form occurs in the homesteads, good management practices must be used where crop choice will be very important to avoid crops that are not tolerant to water logging. The Gf soil can be suitable for RWH&C practices and, in general, for crop production (croplands and homesteads) as it is deep enough (up to 1,000 mm), although its clay content might be too low.

A small percentage of the soils were of the Bainsvlei (Bv) soil form. The clay content in the orthic A-horizon was between 10 and 15%. The clay content increased in the B1- and B2-horizons to around 15 to 30%. The A-horizon was deep, ranging between 300 and 400 mm, with a deep B1-horizon of over 500 mm. The B2-horizon varied between 300 and 400 mm. The A-horizon varied between dark brown and strong brown, with the B1-horizon not varying much between the chromas, which were yellowish red. The Bv soil forms at Krwakrwa were deep with an average effective rooting depth of over 1,000 mm. The Bv soil form is suitable for RWH&C practices and, in general, for crop production (croplands and homesteads), providing that it is deep enough (1,000 mm). The soft plinthic B-horizon could indicate that waterlogging occurs, and therefore the soil could pose a problem to water-sensitive crops in a very wet season.

The Swartland and Sepane (Se) soil that forms the orthic A-horizon in both instances had a lower clay content than the pedocutanic B-horizon of both soils. The clay content in the topsoil was found to be between 10 and 20%, and in the subsoil it ranged between 20 and 40%. The Swartland soils found in the study area were shallow, ranging between 400 and 500 mm, whereas the effective depth of the Se soil forms ranged from 500 to 1,200 mm. The Swartland soils in this region were not suitable for RWH&C practices and crop production, in general, as they were too shallow. The soils occurred near erosion ditches, which showed how susceptible these soils are to erosion. If not managed properly, they can cause major problems. RWH&C practices could be implemented on the Se soil forms, although the signs of wetness indicate waterlogging, and could therefore pose a threat in very wet years. Certain Se soils in the study area are also far too shallow for RWH&C practices, and therefore the depth should be checked first.

A large part of the study area consisted of the Mispah soil form, which was mostly found on the northern and eastern rangelands. The A-horizon was usually shallow with a low clay content of between 8 and 13%, which overlies hard rock. This soil form is not recommended for crop production (croplands and homesteads) due to its shallow depth and low clay content, and is sensitive to erosion. Good care and management practices on the rangelands where the Mispah soil form occurs is needed to prevent overgrazing, which will lead to erosion. Land-use potential is limited to grazing.

A very small part of the study area consisted of the Glenrosa (Gs) soil form, which was mostly found on the rangelands and at a few homesteads. The A-horizon was usually shallow with a low clay content of between 5 and 10%. The lithocutanic horizon was also shallow (200 mm) and very quickly became hard rock. This soil form is not recommended for crop production (croplands and homesteads) due to its shallow depth and low clay content. Good care and management practices on the rangelands where the Gs soil form occurs is needed to prevent overgrazing, which will lead to erosion. In a few isolated cases, Gs soil forms were also observed in a few homesteads on the eastern side of the villages' houses. Other alternative production methods like tower gardens might be a way to produce vegetables.

The Longland soil form was found in the lower-lying areas near water sources, such as natural dams. The orthic A-horizon exhibited low clay content, ranging between 5 and 10%, and the E-horizon had a clay content of around 5%. The soft plinthic B-horizon was usually very shallow (100 to 200 mm). This soil is not recommended for RWH&C practices or any other sort of crop production and should just be left for rangelands. The processes that played a part in the soil formation indicated that the soil is waterlogged with a varying water table.

The soil map presented in Figure 3.1 depicts 119 points augured at Krwakrwa . As already stated, a wide variety of soils occur in the village, ranging from shallow Mispah to very deep Hutton soil forms. The village has very good soils to the eastern side, which have the potential to be very productive under correct management. The abandoned croplands to the southwest of the village consist of very shallow Westleigh, Sepane and Glenrosa soil forms. These soils are not recommended for cropland production due to their restrictive depth and tendency to erode. The tendency towards erosion can clearly be seen by the huge erosion dongas. The croplands to the west of the village consist of patches of 700-mm deep Avalon soils, although patches of shallow Westleigh and Mispah soils occur between the Avalon soil form. This area is not recommended for croplands due to the frequency of the shallow soils. If cropping areas are laid out on these Avalon soil forms, a thorough check of the soils will have to be done to ensure that the croplands do not move into the shallow Mispah and Westleigh soils. It is further recommended that only the croplands to the east of the village be used for crop production. The old croplands that are currently not in use do not have high-potential soils and should be reverted back to rangelands.

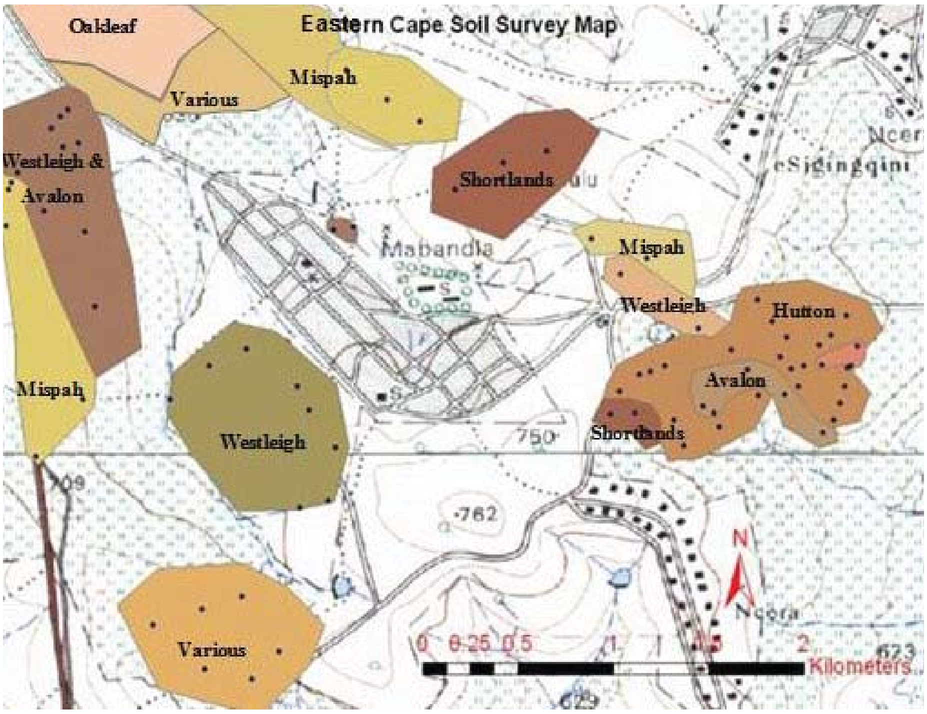



**Figure 3.1: A soil map indicating the dominant soils in Krwakrwa Village**

A variety of soils occur in the homesteads. These range from very shallow Glenrosa to Clovelly, Westleigh, Oakleaf and Avalon soil forms to very deep Hutton soils. In general, most of the soils in the homestead gardens can be used for crop production, except for a few isolated cases where very shallow Glenrosa soils occurred, which should be avoided.

A wide range of soils occur throughout the rangelands. These soils range from deep Avalon and Oakleaf soils to very shallow Mispah and Glenrosa soils. The soils occurring on the rangelands need to be very carefully managed due to their high potential to erode. The erosion ditches that have formed in the centre and to the south and north of Krwakrwa need to be managed to prevent them from spreading.

### 3.2.2 Climate

A climate record for Krwakrwa Village was derived from the climate data recorded at Fort Cox College and Alice. Climate data from an automatic weather station at Fort Cox College is available from October 2000 to the present, whereas climate data from the automatic weather station at Alice is available from 2008. The longer record of climate data measured at Fort Cox College was used as an approximation of the climate at Krwakrwa. Days with no climate records for Fort Cox College were identified and the corresponding climate record for Alice was then used to approximate the climate at Krwakrwa. Monthly means for the various climatic variables were calculated from the new climate dataset. To ensure the integrity of the calculated monthly means used to describe the climate of Krwakrwa, a condition was implemented that at least 90% of the daily values need to be available and that these values need to have passed quality control procedures.

The area is characterised by warm summers and cold winters. The climate is typical for a semi-arid area with a low annual rainfall and high evaporative demand. Minimum temperatures are the lowest during July and the highest during February. Maximum temperatures are the highest during February and the lowest during June. In terms of exceeding temperature threshold values, July is the month with the most minimum temperature recordings below 0 °C and -2 °C, followed by June.

Interestingly, when only considering 0 °C as a threshold, August had more days than June when the minimum temperature dropped below 0 °C (but not lower than -2 °C). A good proxy for the occurrence of frost is when the minimum temperature approximates 0 °C. This threshold can therefore be used as an indication of frost days. Maximum temperature thresholds of 30 and 35 °C are occurring more frequently during the late summer months compared to the early summer months. January is the month with the highest occurrence of maximum temperatures exceeding 30 and 35 °C.

The lowest monthly mean minimum relative humidity occurs during August, while the month in which the mean relative humidity is the highest occurs during December, followed by January. The lowest monthly mean maximum relative humidity occurs during July, while the highest monthly mean maximum relative humidity occurs during February. In general, the distribution of monthly mean minimum and maximum relative humidity is larger during the winter months than during the summer months.

April is the month in which the maximum wind is the weakest. A gradual increase in the maximum wind takes place during the winter months to peak in August, after which the maximum wind strength subsides (with the exception of December) towards April.

Rainfall mostly occurs during the summer months, with the most rainfall occurring during January. May, June and July receive the least rainfall. Daily rainfall exceeding 20 mm occurs most frequently during the mid-summer, being most frequent during January and December. Daily rainfall exceeding 40 mm occurs most frequently during January, February and October. Krwakrwa receives an average rainfall of 569 mm per annum, of which 82% (468 mm) occurs between October and March, and only 18% (101 mm) occurs between May and September. January has the highest average monthly rainfall, and May and July have the lowest average monthly rainfall of 87 mm and 16 mm, respectively. Very low rainfall occurs during May (16 mm), June (21 mm), July (16 mm), August (25 mm) and September (23 mm).

### 3.2.3 Rangelands

**Herbaceous layer**

The herbaceous layer was assessed for two functional traits of the rangeland. The assessment for ability to support livestock production was conducted using a veld condition score according to Berckerling et al. (1995). Then it was assessed for the biophysical functioning of the landscape, as described by Tongway and Ludwig (1996). The landscape was divided into natural rangeland, degraded old lands and bush-encroached old lands. In determining the veld condition score, species composition of the site was determined using the step-point method, and nearest species to the point was identified. Each transect consisted of 100 points, and the data was analysed by the simplified technique (Berckerling et al., 1995), where a rod was dropped after every two steps and the nearest plant species recorded. Herbaceous layer is an important component of rangeland as it provides forage and soil protection to erosion. Fourteen transects of 100 points were made in the whole grazing area.

The vegetation of Krwakrwa adjoins two veld types: the false thornveld of the Eastern Cape and the Dohne sourveld that dominates the Amatole Mountains. The north-eastern parts of Krwakrwa are in the basin of the Hogsback Mountain, and the south-western parts are on the drier side towards Alice. The site is at the base of the Hogsback mountain range. The two neighbouring villages, Krwakrwa and Upper Ncera, share the same rangelands. The communal rangelands are not fenced. Only the cultivated and old lands are fenced since these areas are very important fodder reserves for the winter period. The grazing lands in their natural state are resilient Dohne sourveld due to the high rainfall.

The condition of the veld is still in an excellent condition (81.6%), as shown by the average veld condition score (VCS) of 11 transects (Table 3.1).

**Table 3.1: Comparison between different vegetation types of Krwakrwa communal land**

| Landscape | VCS (%) | GC (ha $AU^{-1}$) | Dominant species | Comments |
|---|---|---|---|---|
| Natural veld | 81.6 | 2.5 | *Eragrostis capensis* *Themeda triandra* | Highly homogeneous vegetation |
| Small camp | 95.1 | 2.1 | *Themeda triandra* | High grazing pressure |
| Degraded old lands | 33.2 | 10.2 | *Sporobolus africanus* | High soil degradation in steep slopes |
| Old lands with bush encroachment | 29.6 | 10.3 | *Cynodon dactylon* | High tree density |

The species composition survey showed that the natural rangeland is dominated by good grasses (decreasers), such as *Eragrostis capensis* (31.4%) and *Themeda triandra* (27.6%). These are species that predominate in veld that is in a good condition and decline in abundance when veld deteriorates in condition through over- or under-utilisation. These species tend to die out in veld that is too heavily grazed, where grazing is extremely lenient and fire is excluded, or where grazing is selective. Decreasers constitute an average of 60.1%, followed by Increaser II species (27.4%) and Increaser III grasses (7.8%). Increaser I species constitute less than all other ecological statuses (3.4%). The species composition was well balanced and the veld was in a good condition. However, there were signs of high grazing pressure as it was observed that the cover was very short and Increaser II species such as *Sporobolus africanus* (14.5%) started to replace good grasses.

The condition of the old lands was in a poor state and had been transformed from the Eastern Province thornveld. The old lands are separated into two forms: those that are heavily encroached by thorn trees (*Acacia karroo*) and those that are degraded and sparsely covered by thorn trees. In areas where the bush is dense, grass species composition is mainly dominated by Increaser II species, mainly pioneer grasses such as *Cynodon dactylon* (33%). The average VCS for this area was 29.6% (Table 3.1). In degraded old lands, vegetation was mainly dominated by the increaser grasses. *Hyparrhenia hirta* was the most identified Increaser I species, constituting 7.7% to the total VCS. The ecological status of Increaser II species comprised a high number of grass species in the assessment (71%), with *Sporobolus africanus* (21.6%), *Eragrostis capensis* (20.4%), *Cynodon dactylon* (7.1%), *Eragrostis racemosa* (6%) and *Aristida congesta* (5.7%) dominating this category. The average VCS of the degraded old lands was 33.2%, with an average grazing capacity (GC) of 10.2 ha per animal unit (AU), which is significantly lower than the benchmark grazing capacity of 3 ha $AU^{-1}$ for the Eastern Cape false thornveld. Therefore, the condition of the veld was considered very poor and the grass species composition was dominated by low forage grasses. Table 3.1 shows average condition scores, grazing capacities and dominant species in different homogeneous vegetation areas of the Krwakrwa communal land.

A small camp was established in 2009 within the natural veld behind the village settlement area that had been used to demonstrate rotational grazing and resting in a previous WRC-funded project. This camp had experienced high grazing pressure since there was no control over it and it showed signs of continuous grazing. However, the previous resting period was not known as these rangelands are communally shared. The average condition score in that camp seemed to be better than in all the other natural veld areas. This could be attributed to the effect of fencing controlling access of unherded livestock.

**Woody layer**

The climate in the villages at the bottom of Hogsback Mountain is considered to have higher rainfall. The veld type, according to Mucina and Rutherford, (2006) was identified as Bhisho thornveld, previously known as the Eastern Province false thornveld, which is classified as mixed veld. The woody vegetation is dominated by *Acacia karroo.* According to the simplified technique, the woody vegetation is classified as *Acacia* thornveld (Berckerling et al., 1995). The bush component of the vegetation is still in its juvenile stage. In accordance with this technique, the bush phytomass in the natural rangeland is less than 1,500 trees ha$^{-1}$, while the density for heavily encroached areas is between 1,500 and 300 trees per hectare that has a low-browsing capacity. The bush component in the old lands is just the opposite of what is happening in the rangelands. Bush encroachment in the old lands is a sign of degraded lands, and the bush phytomass here is between 1,500 and 3,000 trees ha$^{-1}$. Browsing capacity for the natural veld is just 2.7 ha AU$^{-1}$, and in the old lands, it is 1.2 ha AU$^{-1}$.

**Landscape functional analysis**

Landscape functional analysis (LFA) is a vegetation and landscape monitoring procedure that uses rapidly acquired soil surface indicators to assess the biochemical functioning of landscapes. The LFA method involves randomly selecting the starting point and laying out a transect (i.e. 100 m long in this case), as close as possible to the soil surface, straight and taut directly downslope. To measure the width of patches, a 100 m tape was used and laid across the transect. The assessment was done in all landscape divisions of the area. Ten transects of 100 m were assessed comparing the fenced areas and unfenced sites.

The percentage of patches occurring in the old lands and grazing camps in Krwakrwa is presented in Table 3.2. In the areas where the old lands have been planted with legumes and cleared of *Acacia karroo,* the landscape seemed to have more grass patches (38.9%) and *Acacia* seedling patches (38.9%). In these areas, the number of bare patches (11.1%) was small, but the magnitude of the individual patches was big. Forb patches constitute about 11% of the measured landscape. In terms of the soil surface indicators in these areas, there was moderate rain splash protection and high perennial vegetation cover. The few bare patches that exist showed no signs of cryptograms, which indicates the absence of microbial activity in these soils. These bare patches were smooth with very small amounts of decomposed material.

**Table 3.2: Percentage of patches occurring in the old lands and grazing camps in Krwakrwa**

| Landscape | Grass patches (%) | *Acacia* patches (%) | Forb patches (%) | Bare patches (%) |
|---|---|---|---|---|
| Old land with legumes | 38.9 | 38.9 | 11.1 | 11.0 |
| Old land with no legumes | 49.7 | 16.7 | 11.1 | 22.2 |
| Formerly fenced camp | 51.0 | 0 | 7.7 | 40.0 |
| Non-fenced camp | 54.2 | 0 | 4.2 | 41.0 |

In the old lands that have not been planted with legumes or cleared of *Acacia karroo,* the occurrence of *Acacia karroo* seedlings was 16.7%, while bare patches and forb patches constituted about 22.2% and 11.1%, respectively (Table 3.2). In the camp that had been fenced during a previous project in 2009 to demonstrate veld resting and rotational resting or grazing grass, forb and bare patches constituted 51%, 7.7% and 40%, respectively. The unfenced camp closer to the village was characterised by 54.2% grass patches, 41% bare patches and 2% forb patches. With regard to the soil surface indicators, although these camps had a higher number of bare patches, the bare patches were still covered with a lot of cryptograms and decomposed material, which is an indication of a healthy soil. The width of these bare patches was very small in comparison with the width of bare patches found in the abandoned old lands.

## 3.3 BACKGROUND, DEMOGRAPHIC PROFILE AND HUMAN RESOURCES

### 3.3.1 Historic background of Krwakrwa and Upper Ncera

Both Krwakrwa and Upper Ncera are some of the oldest villages in the Eastern Cape, having been established in the 1800s. They are currently under the traditional leadership of Chief Justice Mabandla, who is, in turn, under the leadership of His Majesty King Jonguxolo Vululwandle Sandile of the AmaRharhabe Kingdom. His paramountcy consists of the 40 traditional councils; each presided over by a senior traditional leader. The Royal House of the AmaRharhabe Kingdom, the Mngqesha Royal Place, is located in King William's Town. The communication between the chief and the village is an open-ended relationship. The tribal segregation served as a vital pillar of racial discrimination based on the policies of the former apartheid government. Noteworthy was the creation of rural bantustan or homeland areas for the black majority – an administrative mechanism for marginalising blacks from mainstream socio-economic and political activities (Todes and Turok, 2018). The accompanying battery of repressive policies rendered the homelands overcrowded and poverty-stricken communities devoid of appropriate education, physical infrastructure, and economic and labour market opportunities (Van der Berg and Bhorat, 1999; Todes and Turok, 2018). This promoted temporary labour migration from the homelands for employment opportunities in "white" areas. However, movement was strictly controlled by pass laws (Klasen and Woolard, 2008).

The headmen play a fundamental role within all villages that fall within Chief Mabandla's leadership. If problems arise, the headmen and the village first discuss them among themselves before referring the matter to the chief for a final decision and approval. Not all matters are sent to the chief, since headmen are also given powers to preside over some cases. The villages still maintain their old traditional practices and traditional ceremonies, even though politics are now involved in the administration of the villages. The Krwakrwa and Upper Ncera villages consist of about 300 and 314 households, respectively. The villagers in both villages are isiXhosa-speaking people. The majority of the villagers are adults, since the youth have left in search of job opportunities and better lives in urban areas. All the households have access to electricity, but firewood, paraffin and gas are still used for cooking in some households. The majority use electricity mainly for lighting. People are very poor and cannot afford to use electricity for everything.

### 3.3.2 Demographic data and gender dynamics

The project team members compiled a detailed questionnaire (Appendix 1). The questionnaire was used to collect primary data from the farmers and villagers. The questionnaire was developed or written in English, but translated into isiXhosa (which is the official language of Krwakrwa) during the individual interviews or consultations. The questionnaire was divided into 12 sections, and 163 questionnaires were administered in the two villages (100 in Krwakrwa and 63 in Upper Ncera) from the randomly selected farmers and villagers. Apart from the questionnaire, a few consultations were conducted with some of the individuals in the village. Secondary data was also consulted in gathering data about the village.

*"For the black and especially African majority, suddenly a new dawn broke. After these masses had cast their votes, they still had nothing in their stomachs and their pockets… but they yet had a spring in their step because they knew that a new dawn had proclaimed the coming of a bright day."*

(President Thabo Mbeki, State of the Nation Address, February 2004).

More than 25 years after the dawn of democracy in South Africa, the majority are still struggling to put food on the table. The situation is far worse than during the apartheid regime, since the rate of unemployment in South African has more than doubled in the last few years. South Africa's rural poverty and chronic deprivation may be partly ascribed to the poor endowment in natural resources of the former homeland areas (Perret et al., 2005).

Perret et al. (2005) further mentioned that poverty is rather seen as a product of the political structures whereby rural poverty served the interests of dominant social groups by using low-cost farm labourers and workers for off-farm activities (mining and industry, commercial and domestic services). It will therefore be narrow-minded not to have a look at the social wellbeing of the smallholder farmers and their families within the rural areas. Human and social resources (gender, age, household status, educational background, employment, socio-economic status), natural resources (land and water), and functional and workable institutional arrangements (enforced by institutions, including the private sector and government, within the area) build livelihoods. Based on what is experienced across the developing nation, livelihoods in rural areas are negatively affected, since fathers and youths are expected to leave their rural homes to search for job opportunities in urban areas. Based on the information provided in Table 3.3, it is clear that the residents of Krwakrwa and Upper Ncera need urgent interventions with regard to their living conditions. In a study conducted by Botha et al. (2014b), the population of women was slightly higher (51%) than that of men (49%).

**Table 3.3: Demographic description of Krwakrwa and Upper Ncera**

| Description | Krwakrwa (%) n = 100 | Upper Ncera (%) n = 63 |
|---|---|---|
| **Sex of household head** | | |
| • Male | 36 | 33 |
| • Female | 64 | 67 |
| **Status of household head** | | |
| • Single/never married | 24 | 19 |
| • Married | 36 | 44 |
| • Divorced | 33 | 6 |
| • Widow/widower | 7 | 30 |
| **Household size** | | |
| • Between 1 and 3 | 29 | 24 |
| • Between 4 and 6 | 46 | 40 |
| • Between 7 and 8 | 16 | 29 |
| • Over 8 | 9 | 8 |
| **Age of respondent in years** | | |
| • 15–30 | 7 | 4 |
| • 31–45 | 17 | 13 |
| • 46–65 | 35 | 25 |
| • > 65 | 41 | 21 |
| **Highest qualification** | | |
| • No educational training | 7 | 3 |
| • Below Grade 6 | 33 | 25 |
| • Grade 6–8 | 28 | 51 |
| • Grade 9–10 | 11 | 11 |
| • Grade 11–12 | 10 | 3 |
| • Post-matric | 11 | 6 |

| Description | Krwakrwa (%) n = 100 | Upper Ncera (%) n = 63 |
|---|---|---|
| **Primary occupation** | | |
| • Farmer | 2 | 3 |
| • Pensioner | 51 | 40 |
| • Full-time employed | 13 | 13 |
| • Unemployed | 25 | 38 |
| • Other | 9 | 6 |
| **Monthly household income** | | |
| • R1–2,000 | 74 | 68 |
| • R2,001–3,500 | 13 | 22 |
| • R3,501–5,000 | 4 | 6 |
| • R5,001–7,000 | 1 | 0 |
| • R7,001–8,500 | 4 | 2 |
| • > R8,500 | 4 | 2 |
| **Monthly grocery expenditure** | | |
| • R1–500 | 24 | 25 |
| • R501–750 | 26 | 33 |
| • R751–850 | 20 | 17 |
| • R851–1,000 | 13 | 17 |
| • > R1,000 | 17 | 6 |

This study discovered that living conditions, access to nutritious food, transport and many other things are in a poor condition, and the majority of residents in both villages are women (64% in Krwakrwa and 67% in Upper Ncera). This can be attributed to the fact that most of the men have moved to urban areas in search of job opportunities so that they can provide for their families. According to Mlambo (2018), the increasing inequality and economic disparity within South Africa, poverty and economic hardships further fuel rural-urban migration in the country.

It was discovered that if these people (especially the men) do not get jobs in urban areas, they become involved in the informal economy as hawkers, pavement business owners (selling fruit, vegetables and sweets), rickshaw operators in beach areas, recyclers (e.g. collecting plastic, glass and cardboard), drivers, mechanics, carpenters, barbers, daily labourers and personal servants. The informal economy is huge and expanding across sub-Saharan Africa. It generates 90% of employment opportunities in some countries and contributes up to 38% of gross domestic product (GDP) in others. It supports some of the most vulnerable people in society: women, youth and the rural poor. On the other side of the coin, statistics on the contribution of the informal economy to national and regional incomes is somewhat less impressive and more uncertain, but demonstrates that the informal economy is important to overall income and employment. It is also unfortunate that some will remain unemployed for a longer period until they go back home empty-handed. Those who have the opportunity of getting permanent jobs go back after a few years to fetch their entire families so that they can live together in urban areas. What is of a concern is that those who go back to fetch their families leave their houses behind unoccupied and not maintained. Angelopulo (2017) mentioned that, between 2001 and 2011, South Africa’s urban population increased from 57 to 63%, and cities like Cape Town, Durban and Johannesburg have witnessed a significant increase in the inflow of people from across the country.

Infrastructure is a key element of poverty alleviation. It often acts as a catalyst to development and enhances the impact of interventions to improve the poor's access to other assets (e.g. human, social, financial and natural assets, the impact of which is felt both in the economic and social sectors). Without roads, the poor are unable to sell their output on the market (Gaal and Afrah, 2017). Furthermore, because rural areas lack the critical infrastructure needed for rapid development, they are, to a great extent, disconnected from development that takes place in urban areas; hence, with limited development, people opt to go in search of opportunities. Factors that are responsible for urban migration are not only job opportunities, but include better housing conditions, better education opportunities, rural land tenure and inheritance patterns, better health services, extreme poverty, and seeing or hearing success stories of people that left their rural villages and moved to the cities, and are supposedly "doing well". Nevertheless, what is of great concern is the high rate of unemployment among the youth and those who are still able to work for themselves. Unemployment rates have risen from the beginning of the project to 92% and 89% for Krwakrwa and Upper Ncera, respectively. Botha et al. (2014b) recorded a 75% unemployment rate in Krwakrwa. According to Statistics South Africa (StatsSA) (2020), South Africa's unemployment rate rose to 30.8% in the third quarter of 2020 from 23.3% in the previous period, although below the market expectation of 33.4%. This was the highest jobless rate since quarterly data was recorded, with more people searching for work in the easing of lockdown restrictions. There are limited livelihood activities in both villages, and the majority of residents depend entirely on social grants. The majority of households in both villages earn at most R2,000 a month. Social grants, such as older persons' grants or child support grants, constitute the biggest portion of the income. Despite earning so little, some households spend more than half of their income on groceries. According to Chakona and Shackleton (2019), households who received social grants were more food insecure, had a lower dietary diversity, had lower mean monthly food expenditure and a lower mean wealth index than those who did not receive social grants. The reason for this might be the fact that households have become dependent on social grants and are not doing anything for themselves, which makes it difficult to change their plate of food daily. Secondly, many agricultural lands remain unused for many years in rural areas, including Krwakrwa and Upper Ncera, due to financial constraints, shortage of implements and laziness, among other factors.

### 3.3.3 Access to external income

Apart from those who are working outside these villages and those who are selling their produce, there are limited opportunities for villagers to earn an income. Reliance on social grants is a big concern, especially among the youth, who are not willing get their "hands dirty" by getting involved in agricultural activities. Life, in general, becomes difficult for some households, especially those that rely on social grants for child support. Some households have access to an extra income in the form of money sent home by their children, husbands or wives who went to urban areas to follow job opportunities. Those who have vans ("bakkies") use them as a mode of transport from the villages to town, or even as removal trucks for moving furniture.

## 3.4 FARMING SYSTEMS

### Historic background

The two villages of Krwakrwa and Upper Ncera used to be part on the former homeland of Ciskei, which was formed based on the policies of the apartheid government. Segregation (defined as the imposed separation of groups; the practice of keeping ethnic, racial, religious, or gender groups separate) took place throughout the history of South Africa during the apartheid era. Back then, land was given to the villagers, and they relied heavily on the government for inputs. Farmers then made use of both their croplands and homestead gardens to produce different vegetables, maize and other orchard-related products. The majority received land for a homestead and a cropland via the tribal leadership since the area still cascades under the AmaRharhabe Kingdom.

**Homestead production**

Since the unification of the homeland back into South Africa, the majority of the villagers have been using their homestead gardens mainly for vegetable production for their own household consumption. Selling is not a priority, but they sell some crops when they have surpluses. In homestead gardens with an average size of about 160 $m^2$, several vegetables are produced, such as spinach, beetroot, carrots, cabbage, pumpkin, maize and wild watermelon. A number of households in the village have tanks to do roof water harvesting, so water is available for supplemental irrigation for their crops in the homestead gardens during periods of drought. An extension officer from the DRDAR's office in Alice regularly visits the village to provide the villagers with information and advice. The chief had a good working relationship with the extension officer.

**Cropland production**

The sizes of the croplands range from 1 to 2 ha. The croplands are situated on the southeastern sides of both villages. They are poorly fenced on the outside and individual croplands areas are not fenced at all. Grass strips on the contour separate croplands. Mostly the chief and a few villagers have cultivated their croplands where mainly maize and beans have been planted. The chief has a tractor, while four other tractors are available to cultivate the croplands that belong to the DRDAR. These are circulated among some of the communities. Villagers can also make use of other services provided through the DRDAR, whereby they can pay R1,800 per cropland per person to have their fields ploughed, planted and maintained. Initially, some people paid the requested amount, but the whole process failed in the second year as people did not have money to pay for the service, as they were unable to sell anything due to poor production outcomes.

**Animal production**

Apart from the cropland smallholder farmers, there are also those who do mixed farming (cropland and animal production). They have animals such as cattle, sheep, goats, chicken, ducks and pigs. There is no limitation on livestock ownership (smallholder farmers can have as much livestock as they want) in these two villages. All animals are kraaled at night and released in the morning to graze in the nearby rangelands. Rangelands are communal since all the villages next to each other fall under tribal leadership and are not fenced. According to Botha et al. (2014b), the lack of fencing in the rangelands prevents the introduction of camping systems. The problem of no camping systems leads to the loss of palatable grasses and degradation. Rangeland degradation is of concern for a vast area of the world's rangelands and their value for ecosystem services, including food, water and livelihoods for many of the world's poor (Bedunah and Angerer, 2012). Botha et al. (2014b) discovered that the smallholder farmers and villagers could not accept the limitation of livestock based on the carrying capacity of the rangelands since, in the African culture, a man's wealth is measured by the number of livestock he owns. Villagers do not realise that overstocking, the insufficiency of a grazing system, poor veld management, no camping systems and a shortage of water supplies for animals are the reasons for the identified degradation of the rangelands.

There is an old dipping tank that was built by the former government of Ciskei. It is not in a good condition, but unfortunately livestock owners do not have a choice, so are forced to use it when dipping their livestock. Livestock production contributes to poverty reduction in various ways, as it can increase local food supplies, serve as a source of income and a means for capital accumulation, generate employment, and supply inputs and services for growing crops. Livestock plays a significant role in rural livelihoods and the economies of developing countries as it provides an income and employment for producers and others working in sometimes complex value chains (Herrero et al., 2012).

Herrero et al*.* (2012) further mention that livestock is a crucial asset and safety net for the poor, especially for women and pastoralist groups, and provides an important source of nourishment for billions of rural and urban households. The livestock sector can play an important role in poverty alleviation, income enhancement and risk reduction for poor rural households and is one of the fastest-growing subsectors of agriculture and allied activities.

**General**

For both crops and livestock, due to the long periods of drought, poor financial access, shortage of implements and other farming-related matters, the majority of smallholder farmers in both villages were unable to utilise their croplands to their full potential. Those who use them have implemented some source of supplementary irrigation system since communities are struggling with municipal water taps that run dry for long periods. When the municipality makes water available, it is normally around 04:00 in the morning. That is usually too early for villagers to wake up so that they can collect enough water for supplementary irrigation, drinking, laundry and livestock drinking purposes.

According to Blair et al. (2018), most smallholder farmers in sub-Saharan Africa practise low-input/low-yield subsistence agriculture because of limited assets, including one or more of the following factors: finances, labour and land. This constrains their ability to access markets or compete with market prices, as a result of both demand- and supply-side factors (Wiggins, 2002), including access to inputs and credit systems (Pienaar and Von Fintel, 2014). In an African context, South Africa faces high levels of unemployment and low levels of subsistence farming and informal employment, which threatens socio-economic wellbeing and, in particular, the food security of its households (Pienaar and Von Fintel, 2014).

## 3.5 BIOGAS SYSTEMS: SITE DESCRIPTION

Figure 3.2 shows the geographical proximity of the two villages with respect to the control site at SolarWatt Park on the Alice Campus of the University of Fort Hare. Krwakrwa is 6.6 km and Upper Ncera 9 km northeast of the control site. This distance is sufficiently small to ensure that meteorological conditions measured at the control site are applicable to the conditions at the villages. Two control digesters with full-gas profiling and meteorological measurement capability were installed at the control site. Seven similar digesters were installed at both Krwakrwa and Upper Ncera.

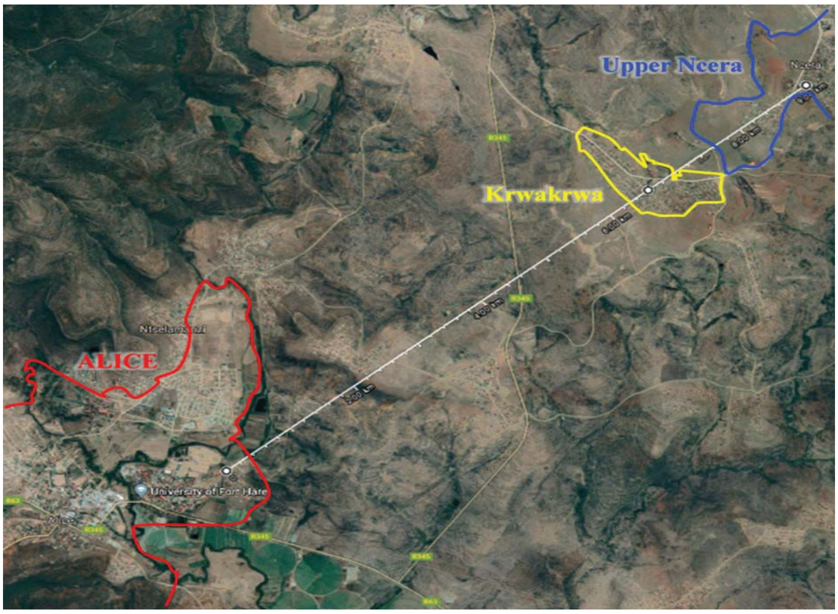



**Figure 3.2: Geographical proximity of the two villages with respect to the control site at SolarWatt Park on the Alice Campus of the University of Fort Hare**

### 3.5.1 Description of the control site: SolarWatt Park

Figure 3.3 shows the two control digesters (one underground and the other above ground). The rationale is to determine the shielding effect of the underground digester from diurnal behaviour due to temperature swings. In addition, the effect of direct normal irradiance or solar energy on the exposed areas of the digesters is also considered.

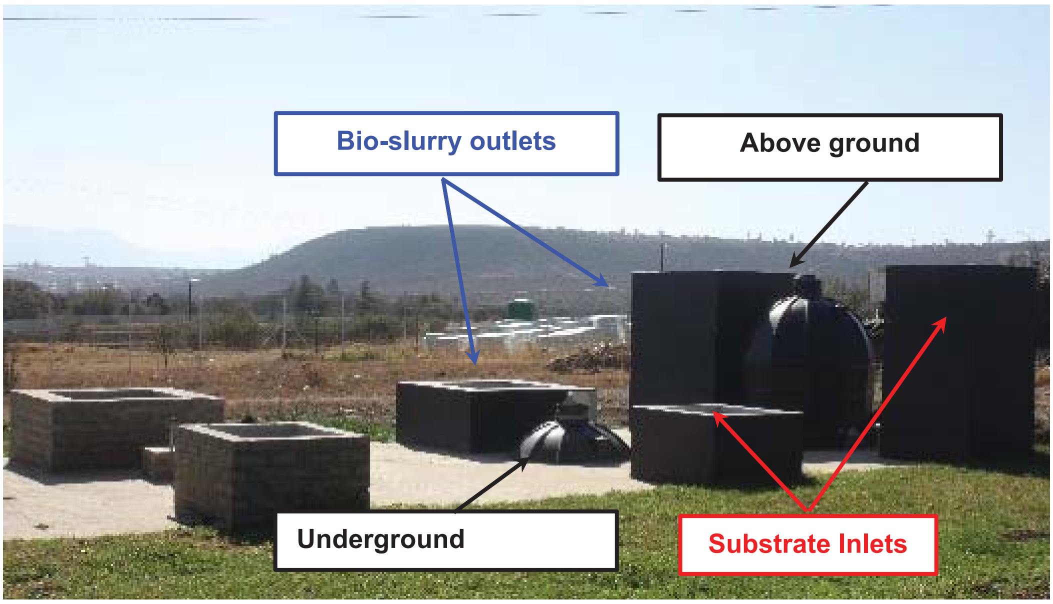



**Figure 3.3: Two control digesters at SolarWatt Park on the Alice Campus of the University of Fort Hare**

### 3.5.2 Gas and temperature monitoring system

To affirm that the biogas digesters deployed at Krwakrwa and Upper Ncera are suitable for domestic use, these control digesters were tested for leaks under high pressure. This was achieved by filling the biogas reactors with $CO_2$ to levels close to 100% $CO_2$. Under these pressures, it is very likely that existing leakages will be enhanced or new ones even formed, with detrimental effects for potential biogas capture. The results obtained from leakage tests indicated that the reactor chambers of the Krwakrwa and Upper Ncera digesters keep the gas levels constant under severe pressure.

The underground and above ground digesters were used as control systems, as well as to determine parameters to evaluate the economic and financial feasibility of biogas digesters for their practical application in Krwakrwa and Upper Ncera. Figure 3.4 shows the temperature of the biogas and substrate within the digester over a retention time of 18 days in November. Also shown is the ambient temperature over the same period. It is evident that the outdoor ambient temperature is a good indicator of the gas and substrate temperatures. This implies that the shielding of the underground installation is not very effective, at least not during the initial digestive period when methanogens are still developing.

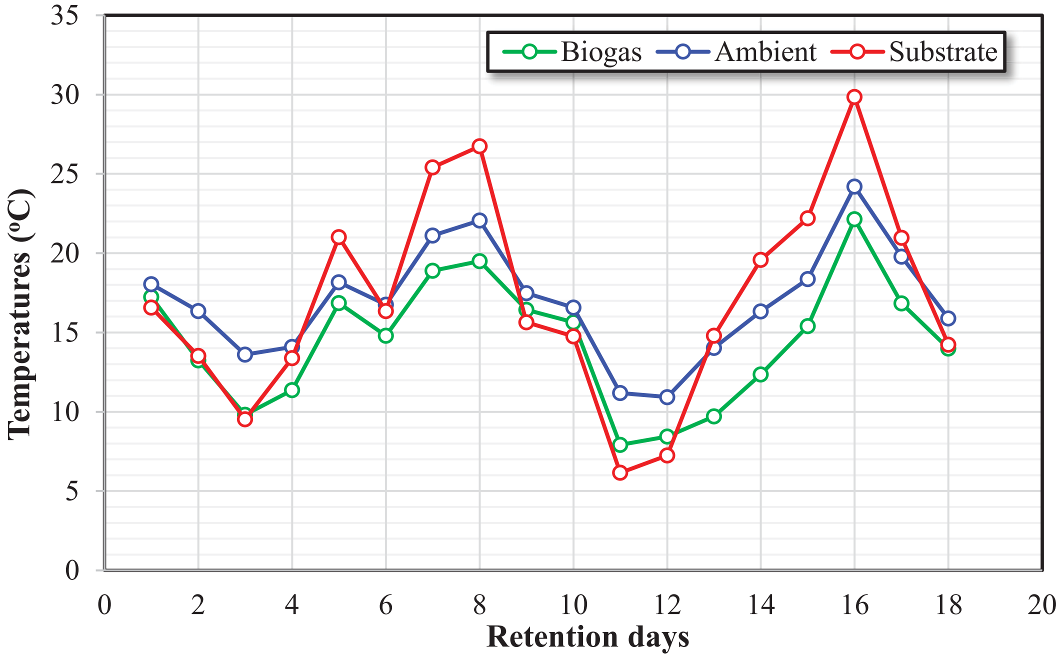



**Figure 3.4:** **Temperature of the biogas and substrate within the digester over a retention time of 18 days in November**

The associated methane and carbon dioxide gas profiles are shown in Figure 3.5. Also shown are the total daily irradiance and the acidity of the substrate. The low temperatures from Day 8 onwards correspond to cloudy and rainy days, which cleared up after Day 12. Although there is a slight dip in the $CH_4$ gas profiles (the highlighted area), it is clear from the recovery volume on Day 12, that the methanogens were sufficiently cultivated to ensure continued growth and hence $CH_4$ production.

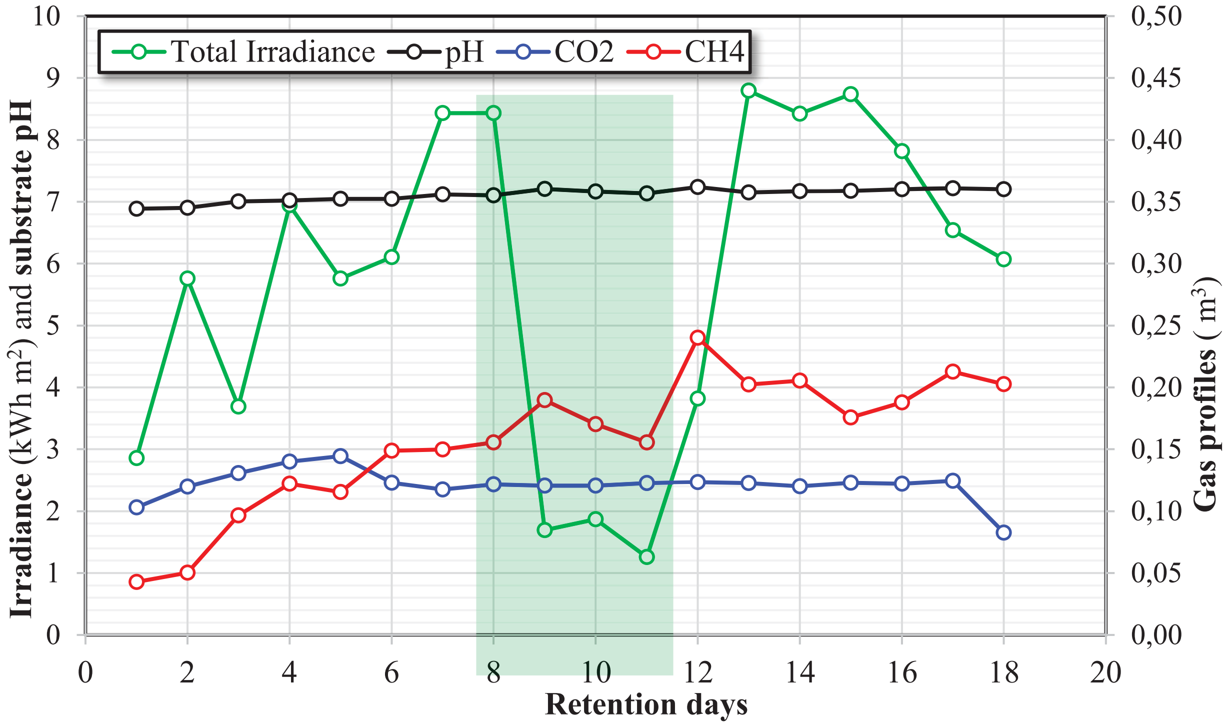



**Figure 3.5:** **Methane and carbon dioxide gas profiles, as well as total daily irradiance and the acidity of the substrate over an 18-day retention period**

### 3.5.3 Description of village sites

Figure 3.5 shows a pin drop at each of the 14 digester sites, seven installed at Krwakrwa and seven at Upper Ncera. These two villages are about 1 km apart, and it would be very interesting to experience the separate institutional arrangements.

**Figure 3.6: Pin drop at each of the 14 digester sites at Krwakrwa and Upper Ncera**

## 3.6 BIOGAS SYSTEMS: METEOROLOGICAL CONDITIONS

### 3.6.1 Meteorological measurement system

This meteorological measurement and data logging system is equipped to accurately acquire a number of solar parameters, in particular, monitoring and logging direct normal irradiance (pyroheliometer tracking), diffuse horizontal irradiance (shaded pyranometer tracking), global horizontal irradiance (pyranometer tracking), infrared radiation (pyrgeometer tracking), global irradiance (pyranometer horizontal), plane-of-array irradiance (pyranometer tilted to 12$^{o}$, ambient temperature, relative humidity, wind speed and direction). Figure 3.7(a) shows the tracking system with on-board sensors and Figure 3.7(b) shows the stationary sensors for measuring wind speed and direction, ambient temperature, relative humidity and spectral distribution of the observed sunlight (spectro-radiometer).

(a) (b)

**Figure 3.7: (a) Tracking system with five sensors measuring various aspects of the incident solar energy; and (b) stationary meteorological sensors, with one pyranometer measuring the plane-of-array irradiance**

These sensors allowed for the measurement of the intensity of various components of the sun, the wavelengths that make up the sun's rays at a specific solar altitude, the heat one gets from the sun and the earth (infrared radiation) and the chill factor brought about by wind speed and direction. These parameters provide a sound basis for all the measurements on the biogas digester systems and the effect of meteorological conditions on their performance.

### 3.6.2 Measured solar data

Figure 3.8 shows the monthly total irradiance or irradiation over the past year under which the biogas digesters were operating. The seasonal trends are clearly visible with an increase in diffuse and infrared irradiation during colder months of May, June, July and August.

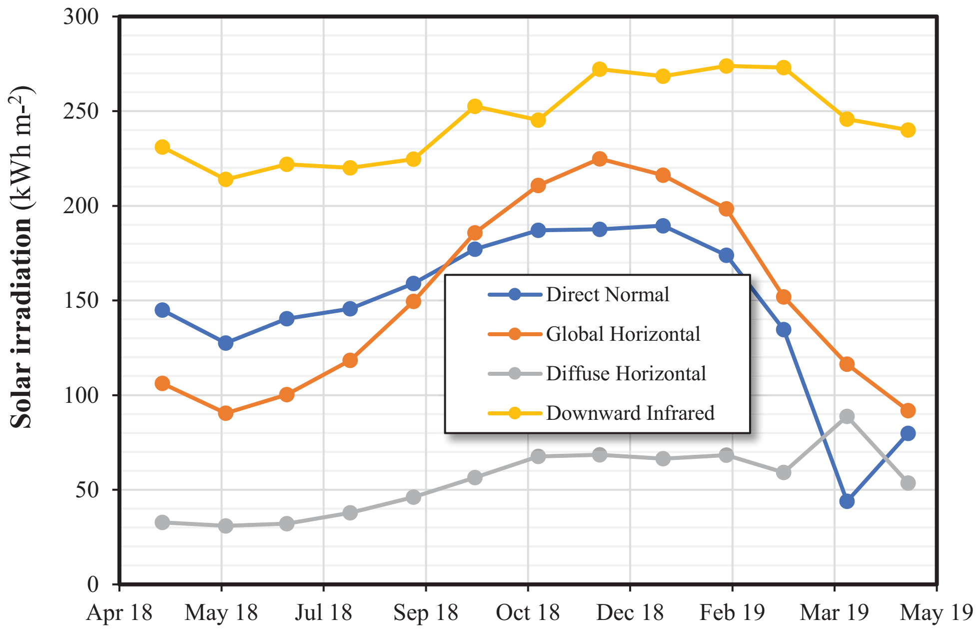



**Figure 3.8: Monthly total irradiance or irradiation over the past year under which the biogas digesters were operating**

### 3.6.3 Measured temperature and humidity

Figure 3.9 shows the average monthly outdoor ambient temperature and relative humidity corresponding to the year portrayed in Figure 3.8.

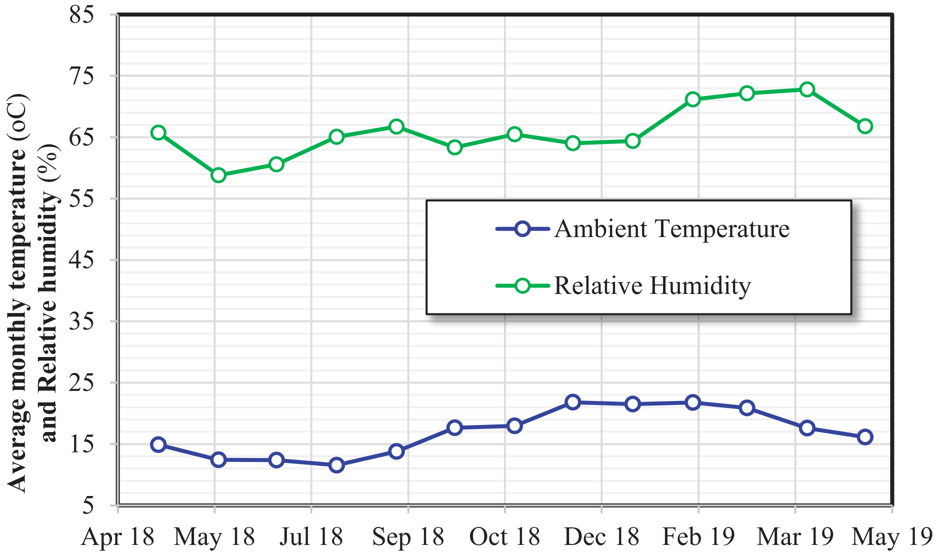



**Figure 3.9: Average monthly outdoor ambient temperature (°C) and relative humidity (%) as experienced by the biogas digesters**

### 3.6.4 Wind speed and direction

The wind rose of Figure 3.10 gives a succinct view of how wind speed and direction are typically distributed at the control site at which the two control digesters are installed. This wind rose was constructed with data over the same one-year period as in Figure 3.8 and Figure 3.9.

Clearly, there are 14.7% calm conditions, as represented by the size of the centre circle. Each branch of the rose represents wind coming from that direction, with north at the top of the diagram. Eight directions are used. The prevailing wind for this test site is an east-south-easterly (102°) wind, which blows for 40% of the year up to a strength of 5.7 m $s^{-1}$.

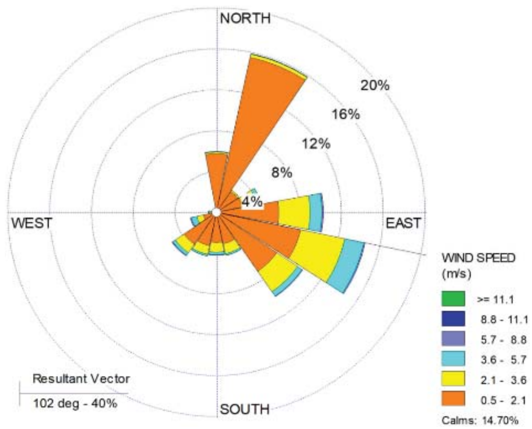



**Figure 3.10: Succinct view of how wind speed and direction are typically distributed at the control site at which the two control digesters are installed**

This is a significant wind factor, which certainly contributes to the chill factor. It stands to reason that underground digesters are well isolated from this effect.

## 3.7 BIOGAS SYSTEMS INSTALLED

Figure 3.11 illustrates the two types of digesters installed in the two villages: (a) balloon and (b) fixed-dome digesters. The continuous organic loading is of the utmost importance for the continued cultivation of methanogens. The balloon-type digester has by far been the most successfully used since it is regularly fed and the produced gas is used on an almost daily basis, thereby stimulating further bacterial growth.

(a) (b)

**Figure 3.11: Two types of digesters installed in the two villages: (a) balloon; and (b) fixed-dome digesters**

## 3.8 SUMMARY

### 3.8.1 Climate

This study area receives an average rainfall of 569 mm per annum, of which 82% (468 mm) occurs between October and March, and only 18% (101 mm) occurs between May and September. January has the highest average monthly rainfall, and May and July have the lowest average monthly rainfall of 87 mm and 16 mm, respectively. Very low rainfall occurs during May (16 mm), June (21 mm), July (16 mm), August (25 mm) and September (23 mm). The area is characterised by warm summers and cold winters. The warmest month is February, while the lowest temperatures are observed in July. This climate is typical of a semi-arid area with a low annual rainfall and high evaporative demand.

### 3.8.2 Soil

The Krwakrwa community has an extremely wide variety of soils, ranging from very shallow Mispah and Glenrosa soils (100 mm) to very deep Avalon and Hutton soils (2,400 mm). The croplands to the east of the community are laid out on high-potential soils. The old croplands to the southwest, west and northwest of the community are spread over medium- to poor-quality soils. Most of these old croplands are not currently in use and it would be better if they could be reverted back to rangelands. A variety of soils occur in the homesteads. These range from very shallow Glenrosa soils to Clovelly, Westleigh, Oakleaf and Avalon soils and very deep Hutton soils. In general, most of the soils in the homestead gardens can be used for crop production. Only isolated cases where very shallow Glenrosa soils occur should be avoided. The rangelands are spread over a very wide variety of soils, ranging from deep Avalon and Oakleaf soils to very shallow Mispah and Glenrosa soils. The soils on the rangelands need to be managed very well as most of them are susceptible to erosion and there are already signs that huge amounts of erosion are taking place.

### 3.8.3 Rangelands

The vegetation of the Krwakrwa and Upper Ncera villages is typical of most rural areas in the Eastern Cape. Grass species composition on the virgin land is good despite constant heavy defoliation and improper veld management practices. The grass in this area lacks the much important rest for the seeding of grass and fodder banks. This is due to a lack of fencing and high stock numbers grazing the veld. The old lands are in a poor condition for any grazing animals. However, goats are benefitting from the *Acacia karroo* that is encroaching the old lands. Some old lands can be used for perennial planted pastures, specifically legumes, using minimum tillage to improve forage quality. The occurrence of larger bare patches in the old lands can be associated with the fact that the land had previously been cultivated, and that led to more vegetation cover loss. These old lands are fairly covered by grass, but the coverage by grasses is less than 50%. The non-existence of cryptogram in the bare patches might be associated with poor soil health that emanates from the nutrient mining that occurred while the areas were still under cultivation. The nutrient loss might have contributed to the minimisation of microbial activity in this area. The existence of a higher percentage of bare patches in the fenced and unfenced camps might be an indication of intensive grazing pressure that occurs due to uncontrolled grazing in these camps. However, even though there is a higher prevalence of bare ground in these camps, their individual magnitude is very small. This might be related to the fact that these areas have never been cultivated. The bare patches also show signs of microbial activity as there is cryptogram and/or organic material in most of the bare patches.

### 3.8.4 Socio-economic conditions

Age distribution indicated that mainly the elderly stay in the rural villages as the youth have moved to urban areas for job opportunities. The majority of households had access to basic education and some have even reached tertiary levels of education. The majority of residents depended on social grants (e.g. older persons' and child support grants) and there was a high rate of unemployment in both villages. Most of the older persons' and child care grants were spent on groceries. Clothing, education, agriculture and health were always a low priority in the household budget. Since villagers do not budget for agricultural production, it has mostly collapsed. The poor farming systems used do not support good production, and where production was done in the homestead gardens and croplands, the yields were low and of an inferior quality. Access to basic needs such as roads, housing and clean water was a concern. Roads were difficult to access during rainy days, since they were gravel roads with potholes, and were slippery when wet.

### 3.8.5 Biogas production

Seven bio-digesters were installed at Krwakrwa and another seven at Upper Ncera. Balloon and fixed-dome digesters were installed for demonstration purposes. Detailed studies on biogas production were conducted at the University of Fort Hare.

# CHAPTER 4: SITUATION ANALYSIS OF INSTITUTIONAL ARRANGEMENTS, ORGANISATIONAL STRUCTURES AND THE ROLE PLAYED BY EXTENSION SERVICES IN THE SELECTED VILLAGES

## 4.1 INSTITUTIONAL ARRANGEMENTS FOR IMPROVED AGRICULTURAL PRODUCTION

In most of the rural areas, the failure of agricultural development can be attributed to the lack of functional and workable institutional arrangements. Agricultural policies and institutional arrangements for policy implementation should strive to become more conducive to diffusion and the establishment of agricultural innovations. Furthermore, both the capacity and quality of extension and advisory services need to be improved, as well as different options for organising smallholders and increasing their access to appropriate agricultural associations that could accommodate and better voice their interests in society (Haug et al., 2018). Agricultural markets, credit institutions, institutions that disseminate research and extension services are the various institutional arrangements that support production in the agricultural sector. Access to these institutions and the services they provide is therefore vital for the development of the sector (Abraham, 2015).

Improved, functional and workable institutional arrangements play a pivotal role in supporting farmers to communally manage their agricultural resources, including more efficient production and enabling farmers to manage their individual use rights better. The whole process will continue either based on the effectiveness of the selected committee or through the assistance of the extension officer. Based on the above information and in an endeavour to achieve the objective of the project, it was agreed from the beginning that it would be necessary to explore institutional arrangements and analyse them in terms of how they affect the livelihood sustainability of the smallholder farmers and their households in the selected study areas.

## 4.2 MATERIAL AND METHODS

Despite trust and collaboration that had already been established with all the smallholder farmers and villagers in a previous project, it was important that further consultations be held. At the beginning, or when villages were selected to be part of the project, they were informed of the aims and objectives of the project. They showed an interest in the study and agreement was reached to assist in achieving its aims. Nevertheless, before the agreement could be reached, a number of consultations were held with tribal leaders, village leaders, farmers' groups and villagers in general. Furthermore, the first step of this consultation processes was to develop terms of reference that would include the scope, purpose, intended recipients and structure of these principles, as well as the format of the consultation process, taking into account existing, past, functional and dysfunctional institutional arrangements.

Substantive meetings and discussions were held with everyone in the two villages. The aim of those gatherings and meetings were to come up with solutions for different challenges, such as management, leadership, and the social, economic, political and institutional environment. Despite the fact that there are no universally applicable solutions to all problems or challenges, it is possible to learn from others' experiences and come up with solutions to address such challenges. For that reason, it becomes fundamental to have a decisive agreement on the way forward. Nevertheless, it was agreed that a number of mixed-method approaches, which involved collecting, analysing and interpreting the data, be used to gather both primary and secondary data.

A desktop literature review was conducted on secondary data, followed by the collection of primary data. Primary data included one-on-one discussions, group discussions, consultation with the tribal council and a meeting with the Council of the Chairpersons. The Council of the Chairpersons is a committee formed with chairpersons from all 13 villages that fall within the leadership of Chief Mabandla. Their main objective is to assist the tribal leader and the headmen with the running of the villages and to advise the chief on certain issues. Well-structured questionnaires with both open and close-ended questions were also used to collect primary data.

## 4.3 DATA ANALYSIS

The use of the mixed-methods approach to data collection produced both quantitative and qualitative data. The quantitative data was analysed using descriptive statistics in Statistical Package for Social Science (SPSS version 24) and Microsoft Excel. Qualitative research is an approach for exploring and understanding the meaning individuals or groups ascribe to a social or human problem (Creswell, 2014). This can play a crucial role when exploring factors such as socio-cultural and socio-economic perspectives that describe the perceptions, attitudes or behaviours of consumers and other food chain actors at local levels (Claasen et al., 2015). Using mixed-methods research can further broaden these insights by combining qualitative and quantitative research approaches during data collection, analysis, the integration of findings and the drawing of conclusions (Tashakkori and Creswell, 2007).

## 4.4 RESULTS AND DISCUSSION

### 4.4.1 Identification of institutional arrangements

The final institutional arrangements agreed upon with the smallholder farmers and/or villagers in Krwakrwa and Upper Ncera, after a series of engagements with everyone involved, are presented in Table 4.1. The M&E system was as follows:

- Assist with the whole planning process (as an important element when determining priorities)
- Set up alignment instruments for institutional arrangements (such as results agreements, strategic management and the selection of responsible committees)
- Develop outputs and outcome indicators as a measurement of the success of the implemented institutional arrangements
  Provide feedback on the progress made (an effort to allow for ongoing learning and the reinvention of the modus operandi in the farming sector)

**Table 4.1: Institutional arrangements adopted and implemented by villagers in Krwakrwa**

| Rule | Formal | Application area | Enforceable | Responsible authority for implementation | Consequences for non-adherence | Measures to resolve non-adherence | Functional | Impact on production |
|---|---|---|---|---|---|---|---|---|
| Anyone is allowed to have an unlimited number of livestock. | Yes | Rangelands | No | No one, since there is no limit | None | None | Yes | Poor quality livestock production resulting from overgrazing and lack of palatable grasses. |
| Vaccination of livestock should be done according to the timetable of the responsible officer. | Yes | Rangelands | Yes | Livestock Committee together with the Village Committee | The guilty person will be fined based on the decision of the Committee. | Refer the matter to the chief and the Village Committee | No | Non-vaccinated animals are not allowed to leave the premises of the owner.<br>Increase in diseases since not all can afford to vaccinate their livestock due to financial constraints. |
| All villagers are allowed to use the rangelands freely, but are prohibited at all times to use other villages' rangelands. | Yes | Rangelands | Yes | Chief and the Committee of Headmen | Livestock will be impounded and put in the *"skeat"*[1] until the person pays. Fine will now include daily costs for storage and feeding. | Failure to adhere to time frame given, livestock will be transported to King William's Town for reselling and to repay the costs. | No | Borders of the village are poorly fenced, which makes it extremely difficult to control the livestock. |

[1] *Place used by government to lock or keep stray animals from the roads or places where they are not supposed to be.*

| Rule | Formal | Application area | Enforceable | Responsible authority for implementation | Consequences for non-adherence | Measures to resolve non-adherence | Functional | Impact on production |
|---|---|---|---|---|---|---|---|---|
| All the rangelands, including camps, should be fenced and closed. Furthermore, rotational grazing should be practised at all times. | Yes | Rangelands | It used to be but now it is not. | Headmen and the Village Committee | Fine will be imposed on those found guilty. | The police will be called to assist in resolving the issue, but currently nothing is happening since no camping systems are in place. | No | Lack of fences and rotational grazing result in the veld being in a poor condition with low grazing capacity. |
| No livestock is allowed to graze along the main road because it will cause accidents. | Yes | Rangelands | Yes | Chief and the Headmen Committee | Livestock will be captured and the owner fined. | Livestock will be kept in captivity until the owner pays, including additional costs for storage. | No | It does not suppress production as such, but promotes responsibility because livestock causes accidents on the road. |
| No pigs and chicken are allowed to roam the streets freely at all times. | Yes | Rangelands, croplands and homestead gardens | Yes | Village Committee | Fine will be imposed on those found guilty. | Before 1994, the chief and the law enforcement officers were called. | No | Livestock destroys crops in the croplands and homestead. In rangelands, pigs destroy palatable grasses. |
| Everyone is free to collect cow dung around the | Yes | Homestead | Yes | Village Committee and | Village Committee will decide on the penalty. | Village Committee will pass the case to | Yes | As part of the tradition, no one can enter |

| Rule | Formal | Application area | Enforceable | Responsible authority for implementation | Consequences for non-adherence | Measures to resolve non-adherence | Functional | Impact on production |
|---|---|---|---|---|---|---|---|---|
| village, but needs to seek permission from the livestock owner where animals are kraaled. | | | | affected individuals | | the tribal authority for a final decision. | | anyone else's kraal without permission. |
| No one is allowed to cut fences anywhere in the village. | Yes | Rangelands and cropland | Yes | Village Committee | Fine will be imposed on the person. | Chief and his Committee of Headmen get involved. | No | Boundaries of the village are poorly fenced and have been in a bad state since they were last fenced in the 1980s. |
| No trees should be chopped down at any time. If need be, permission should be obtained from the chief of the village. | Yes | Rangelands | Yes | Chief and his Committee of Headmen get involved. | Fine will be imposed on the culprit. | | No | Production was not suppressed, but the rule helped to control deforestation. |
| During the planting season, everyone must make sure that there are no trespassers in the croplands. | Yes | Croplands | Yes | All the elderly people in the village who have croplands | All trespassers will face a fine | Both the chief and the police will be informed and livestock caught will be sold to recover costs. | No | Livestock destroys crops if they are not shepherded. |

| Rule | Formal | Application area | Enforceable | Responsible authority for implementation | Consequences for non-adherence | Measures to resolve non-adherence | Functional | Impact on production |
|---|---|---|---|---|---|---|---|---|
| No fires are allowed in the croplands, especially after harvesting. | Yes | Croplands | Yes | Village Committee and the chief | Whoever commits this crime will be fined. | Chief of the village will make a final decision whether to involve the police or not. | No | It is not currently implemented, because very few people are making use of the croplands. |
| Every beneficiary is fully responsible to feed the bio-digesters as requested. | Yes | Bio-digester | Yes | Village Committee and project team | | Project team will take a final decision | Yes | Not suppressing production, but promoting production through the use of biogas effluent. |

All institutional arrangements were continuously implemented, evaluated and monitored, despite challenges that were beyond the project team's capabilities. These institutions are referred to regularly throughout the rest of the report. They comprise those institutional arrangements that were discussed, suggested and agreed to with the smallholder farmers and/or villagers for the sake of the development and improvement of agricultural production in the village. Botha et al. (2014b) experienced many challenges with regard to the implementation and monitoring of institutional arrangements in Krwakrwa. Those who believe in traditional leadership supported the implementation of institutional arrangements, but those who oppose such leadership did not. Nevertheless, the aim of this study was to make sure that everyone understood the importance of the institutional arrangements, and their monitoring and evaluation. Helmer and Hespanhol (1997) emphasise the fact that such investigation or monitoring will provide an idea of whether there are functional or dysfunctional institutional arrangements and if everyone adheres to them. Institutional arrangements are essential to liberate and further develop resources. Therefore, vibrant institutions and institutional arrangements are crucial to sustaining working relations in these villages. Moreover, monitoring and evaluation was done closely with the smallholder farmers and/or villagers after they were implemented. During the process, the project team agreed that, whenever necessary, changes would be made in the implementation and evaluation of these institutional arrangements, provided that there was a need to do so. For example, there was an institutional arrangement that deals with dead livestock. It clearly stated that anyone who sees a dead animal anywhere in the village needs to inform the headman or chief immediately so that the owner can be traced and informed. However, it was unanimously agreed that this should be removed from the list of institutional arrangements, but should rather be used as a general norm for reporting any incident within the village.

Subsequently, the smallholder farmers and/or villagers adopted the institutional arrangements. It was important to continuously monitor and evaluate their adoption and implementation in the villages so that their effectivity could be determined. From the onset, all relevant stakeholders, including individuals in the village, smallholder famers, traditional leadership and political leaders (ward councillors and committees, in particular), were consulted every step of the way with the aim of assisting in the implementation, monitoring and evaluation of the institutional arrangements. The section that follows covers the processes and/or procedures used for monitoring and evaluation and the improvement of these institutional arrangements.

### 4.4.2 Monitoring and evaluation of institutional arrangements

The careful and detailed monitoring and evaluation of institutional arrangements within Krwakrwa was essential to ensure that all the processes were followed and all problems that arose were dealt with in time. Effective M&E also facilitates the integration of learning from previous adaptation interventions into emerging planning and implementation. Effective M&E activities should make provision for flexibility to address unexpected challenges, compare institutional structures and results across different interventions and locations, and promote learning and debate between the farmers and/or villagers. A key step in implementing M&E frameworks that specifically target institutional arrangements is to clearly define both the particular institutional arrangements and the intervention that responds to lack of adoption and other possible outcomes (Figure 4.1).

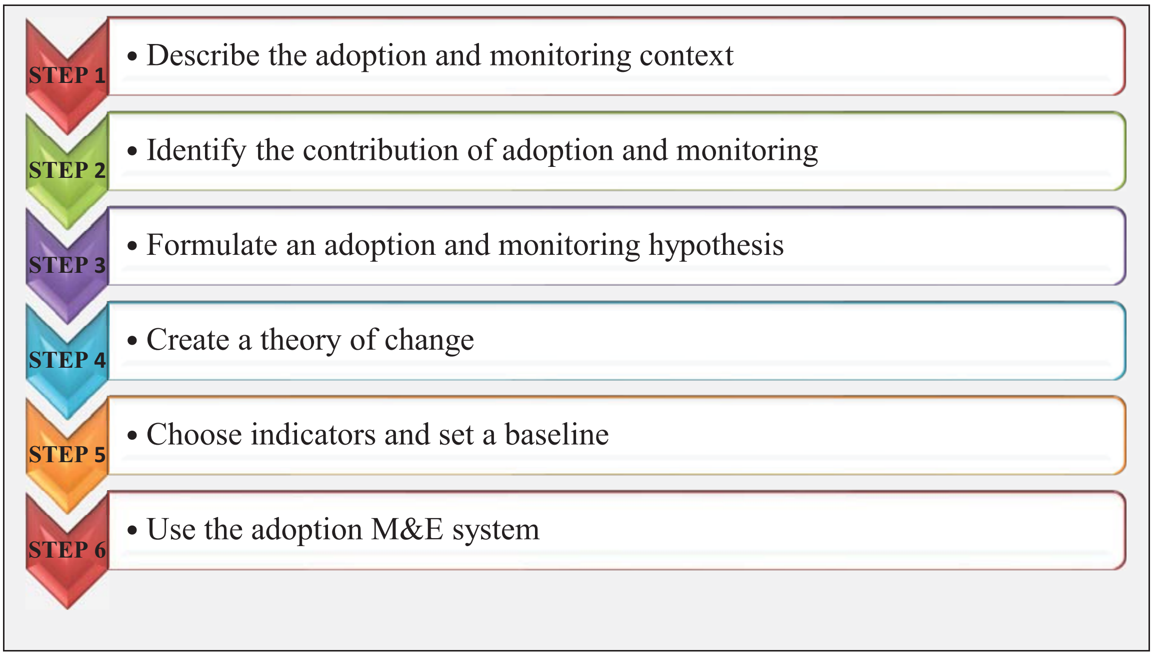



**Figure 4.1: Steps adopted and followed during the monitoring and evaluation process**

The six steps mentioned above (Figure 4.1) are discussed or explained further so that they can provide a broader sense of understanding to everyone and how they were implemented during the whole process.

**Step 1: Describe the adoption and monitoring context**

The first step is to describe the adoption and monitoring context through a comprehensive assessment of risks and vulnerabilities. This assists in identifying factors that can influence an adaptation intervention, both directly and indirectly, to better describe the challenges of the farmers and/or villagers in implementing and enforcing these institutional arrangements. When making use of vulnerability assessments, it is vital that the data used to set the baselines is adequate and accurate, that the key obstacles and enabling factors are identified, and that gaps in the vulnerability assessment are identified.

**Step 2: Identify the contribution of adoption and implementation**

The second step in designing an M&E system for adoption and monitoring is to identify the contribution of adoption that the intervention is designed to deliver. Identifying the contribution of adoption and monitoring can be challenging because of the diversity of activities, which have relevance for adoption. There is no blanket solution for adoption and monitoring activities, since each intervention must be context specific. Therefore, the adoption and monitoring of institutional arrangements are best described by the nature of their objectives.

**Step 3: Formulate an adoption and monitoring hypothesis**

The third step is to formulate an adoption and monitoring hypothesis. This was only done once with the aim of clarifying how the intervention contributes to one of the dimensions of institutional arrangements in its adoption and monitoring. An adoption hypothesis is a testable statement that describes how each outcome addresses specific risks or vulnerabilities.

**Step 4: Create a theory of change**

The fourth step, once the adoption and monitoring hypothesis for each intervention has been drafted, is to create a consistent theory of change that links the adoption activities to the adoption and monitoring outcomes. The theory of change tracks the conditions needed to reach the adoption objective by breaking them down into achievable steps. Establishing the desired chain of events is useful to understand the function of an intervention and monitoring its intervention.

**Step 5: Choose indicators and set a baseline**

The fifth step is to choose indicators and set a baseline. The institutional arrangements impact analysis must be reflected in the indicators. Indicators should be informed by the vulnerability assessment and should target the objectives of the adoption intervention. M&E for the institutional arrangements analysis often requires more qualitative assessment than is the case for mitigation interventions, which can be technically challenging.

**Step 6: Use the adoption M&E system**

The final step is to use the adoption M&E system. It is therefore important to ensure that the indicators are monitored consistently and frequently, that the data is collected from the relevant sources, and that the process has clearly designated roles, which are understood by the relevant parties.

The M&E system that has been introduced, used and adopted for this report was influenced by the six-step M&E system initiated by Spearman and McGray (2011) as part of their adoption projects in rural human settlements. These steps are very important and were carefully implemented not to miss any crucial and relevant information. These steps will even be used in the next assessment in the village.

### 4.4.3 Institutional arrangements' SWOT analysis

During the process of monitoring and evaluating the institutional arrangements, the project team determined it necessary to also identify their internal strengths and weaknesses, as well as their external opportunities and threats. The strengths, weaknesses, opportunities and threats (SWOT) analysis was done by asking farmers and/or villagers their opinions regarding the institutional arrangements. More than 96% of the interviewed farmers and/or villagers managed to do their own SWOT analysis as follows:

**Strengths**

- They guide everyone, instil peace among people and promote stability in the village.
- They reduce the level of lawlessness in the village.
- They favour the development of grass roots collective action in the village[2].
- They allow the farmers and villagers to articulate and act on their priorities, but they always fail.
- They play a significant role in determining the efficacy of a given set of technological interventions.

**Weaknesses**

- Dependency syndrome.
- Lack of or poor leadership.
- Some people are not taking the institutional arrangements seriously.
- Not all institutional arrangements are enforceable.

**Opportunities**

Mentioning opportunities: It becomes very difficult for the villagers to express themselves about the opportunities that the institutional arrangements introduced to their working environment. One farmer mentioned that these institutional arrangements brought back a sense of self-introspection because they reminded him of what they used to do before the 1990s.

[2] Here two types of collective action are distinguished: *cooperation*: bottom-up, farmer-to-farmer collective action, and *coordination*: top-down, agency-led collective action.

The farmers were able to adhere to any institutional arrangement or law that governed their village during those days, but unfortunately, freedom destroyed everything and increased lawlessness, especially in the rural areas. It was further mentioned that these institutional arrangements had brought a sense of ownership to farmers and/or villagers since they can now manage their livestock and croplands, guided by these institutional arrangements. Farmers further mentioned that institutional arrangements brought changes and law to the village, and brought a sense of stability to the divided village.

**Threats**

- Lack of respect towards each other and towards the traditional leaders.
- Ignorance and negativity.
- Discouragement by other people.
- Poor adoption and implementation of institutional arrangements.
- Political interference.
- Lack of dedication and self-respect.
- Dependency syndrome.

Despite the outcomes of the SWOT analysis, especially the threats and weaknesses, farmers and/or villagers made some suggestions to improve or implement the institutional arrangements.

Their suggestions were as follows:

- Give traditional leaders, together with the Village Committee, more powers since the police takes its time to come or resolve problems in the village.
- Bring in harsh penalties so that those who break the institutional arrangements can be given severe penalties.
- Go back and promote the spirit of ubuntu once again.
- Hold monthly meetings where the importance of institutional arrangement can be emphasised.
- Introduce a forum that will enforce the institutional arrangements.
- Engage people by visiting them door-to-door to explain the arrangements and hear their views.
- Provide all the leaders in the village, especially the selected committee members, with training in terms of how to deal with the different situations they are facing.

It became very difficult to understand the smallholder farmers and/or villagers of Krwakrwa because they were able to provide suggestions on how to improve the implementation of the institutional arrangements within their village, but very few of them remembered those that were agreed upon and put in place. Continuous engagement, as requested, was implemented because the success of the project lay within their involvement, self-sacrifice and the dedication of everyone, including the project team, stakeholders, farmers and/or villagers, and the traditional and political leaders in the vicinity of these villages.

### 4.4.4 The impact of the institutional arrangements on production in selected villages

Effective agricultural production can be used as tool that can change the lives of many people and reduce poverty. Although agriculture is the main economic activity in villages and rural communities across South Africa, including Krwakrwa and Upper Ncera, the communities in these two villages are not engaged in agricultural activities despite having their own fields where they can produce for themselves. The latter comes especially to those who leased their lands to others, lands remaining fallow (lands not used for a long period due to financial constraints) or due to the lack of implementation of effective institutional arrangements. Despite having leadership (different types of leadership, including traditional, political, village-based and livestock leadership), there were some people who were not adhering to the institutional arrangements until some were proposed to them, which were adopted by everyone.

The suggested institutional arrangements were even accepted and adhered to by all leaderships in the two villages. However, there were those individuals who had negative thoughts and were not adhering to the institutional arrangements. What was unfortunate for them was that a joint committee had been established to make sure that these institutional arrangements were put into law (practice) and adhered to by everyone. Failure to do so meant that the law-breakers would face the full might of the law. Figure 4.2 sums up all the life-changing roles of the adoption of efficient, functional and workable institutional arrangements in the two study sites.

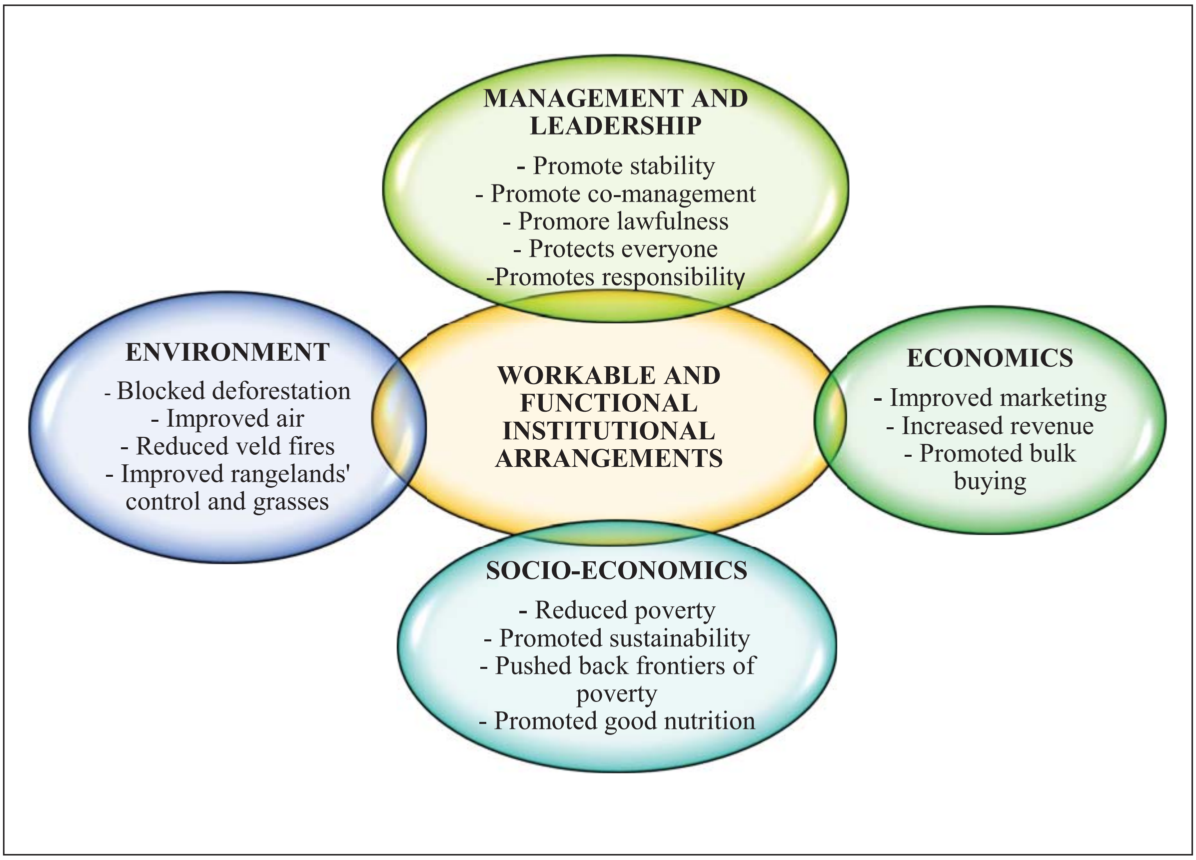



**Figure 4.2: Components that flourished due to the adoption and implementation of institutional arrangements**

Four components can be mentioned that were improved by the implementation and adoption of institutional arrangements. Firstly, management and leadership was one of the issues that was identified as hindering the development of smallholder farmers, but since they were capacitated, their skills improved significantly. Secondly, they are now able to manage their finances, sell their produce on established markets, improve their revenue and save costs by buying in bulk (especially seeds, seedlings, fertilizers and livestock medication). Thirdly, they never had a nutritious plate of food, and that had a negative effect on their health status (not only for adults, but for everyone). They are now able to produce quality, nutritious and healthy food for their families. Lastly, the environment has improved significantly. Trees are no longer cut down and animals can use them as shelter against the hot sun. The air that they breathe is no longer contaminated, since the burning of wood, trees and veld has stopped. Rangelands now have good and palatable grass for livestock, which reduces soil erosion.

They improved agricultural production or activities in the selected areas, whereby smallholder farmers were now able to sell their produce on established markets. The approach championed in this study indicates agriculture as a means of livelihood diversification that connects the economic improvement, as well as the socio-cultural and environmental underpinnings of sustainability.

At the beginning of the project, some of the smallholder farmers, including the villagers, were sceptical and had a limited knowledge or understanding of what effective agriculture can offer or do for them if it is implemented together with functional and workable institutional arrangements as the yardstick. They did not initially realise what economic and life-changing opportunities they would have once they committed themselves to being part of the whole process. In conclusion, institutional arrangements can provide small producers with an array of services, including improving market access and strengthening small producers' negotiating power, enhancing access to and the management of natural resources, and improving access to information and knowledge.

#### 4.4.5 The role of leadership and the impact of the implementation of institutional arrangements

For years, the role of traditional leadership in various developments across the whole of Africa has been a topic of extensive debate and discussion. The institution of traditional leaders has been at the centre of controversies for almost two decades of South African democracy, and its prevailing nature and practices have been repeatedly characterised as undemocratic and/or inimical to democracy (Ngcobo, 2016). Nevertheless, in modern times, traditional leadership continues to exercise an influence in the political, social and economic spheres. In South Africa, one finds them being directly involved in politics and elected as Members of Parliament. There are many such traditional leaders across Africa and South Africa. Such a leader is the traditional leader of the two villages and 11 other villages, and is forever present in all the activities that take place within his villages (Figure 4.3).

(a) During the signing of the MoU.

(b) Attending a meeting at the village hall.

(c) During a production meeting for homestead gardens.

(d) Controlling weeds in the communal croplands.

**Figure 4.3: Traditional leader attending meetings and other project-related activities**

In modern times, it is difficult to come across a leader who suffers for the benefit of his people. Most of the time, smallholder farmers use his implements to prepare, plough and plant their croplands without paying anything, just buying diesel for the tractor. The leader of these villages should be applauded for his dedication and selflessness on behalf of his people.

## 4.5 ORGANISATIONAL STRUCTURES WITHIN THE VILLAGE AND THEIR ROLES

Rural development is a complex process as it involves the continuous reorientation and adaptation of traditional values, practices and institutions to incorporate increasing the corpus of scientific knowledge and technologies to enhance the quality of life and welfare of the people (Bhaker, 2014). That is why there is a need for organisations and/or associations in rural areas. Their aim should be to enhance the living conditions of the people. These organisations and/or associations can either be private or be run by people from outside the village. Their roles and functions can differ according to their focus. A number of researchers have highlighted the significance of community-based organisations (CBOs) and non-governmental organisations (NGOs), and the contribution these organisations make in national, social and economic development, in general, and rural communities, in particular. They function as charitable or religious associations, mobilise private funds for development initiatives and programmes, raise awareness and influence policies in pursuance of the ideals of democracy and good governance, and undertake diverse humanitarian projects that could improve the lots of the grassroots organisations (Ngeh, 2013). Table 4.2 provides a list of such organisation that are found, or that used to be found, in the two villages.

**Table 4.2: List of organisational structures within the villages of Krwakrwa and Upper Ncera and their functions**

| Government departments | Function or purpose | Meet their responsibilities or not |
|---|---|---|
| AmaBhele Tribal Authority | • Promotes and preserves the culture and tradition of communities<br>• Promotes the preservation of the moral fibre and regeneration of society<br>• Promotes the social cohesiveness of communities<br>• Promotes socio-economic development<br>• Promotes service delivery<br>• Contributes to nation building<br>• Promotes the social wellbeing and welfare of communities<br>• Promotes peace and stability among the villagers | • They try to execute their roles and/or mandates at all times, but challenges come from local politicians who claim not to recognise traditional leaders despite the Constitution being clear on such issues.<br>• Lack of a clear understanding as to where power lies makes it difficult for traditional leadership to execute their duties freely without interference from politicians and some individuals who are against them. |
| Vukani Mabhele Agricultural Corporation | • Unites the smallholder farmers within Krwakrwa Village.<br>• Functions as an NGO for the development of the farmers in the village. | • Poor management and misuse of funds led to the downfall of the organisation.<br>• Mandate was not well executed by those that were trusted to lead.<br>• Due to its poor leadership, agricultural production was negatively affected, resulting in many croplands not being used to their full potential. |
| Krwakrwa and Upper Ncera Wool Growers' associations | • Unite all sheep farmers within the villages and work closely together. | • The extension officer formed associations after realising that sheep owners were unable to sell their wool once their livestock had been sheared.<br>• For the past years, farmers were happy about what they have received after selling their wool. |
| Tyhume Agricultural Corporation | • Promotes agricultural production in both homesteads and croplands by preparing the lands, and planting and harvesting on behalf of the farmers. | • Due to non-payment by smallholder farmers, the organisation collapsed. |
| Krwakrwa Adult Centre (established in 2000) | • Cares for the elderly in the village. | • Provides both breakfast and lunch to the elderly people in the village.<br>• The main problem is the cutting of funds from the Department of Social Development, which sometimes led to elderly people not being able to receive any food. |

| Government departments | Function or purpose | Meet their responsibilities or not |
|---|---|---|
| Upper Ncera Adult Centre (established 2005) | • Cares for the elderly in the village. | • Continues to execute its duties even during difficult times.<br>• Now and then receives a donation from one of the local women who is married to a foreign citizen. |

Those who are appointed to lead certain committees or organisations within the villages do not possess any leadership skills. That is detrimental to the development of smallholder farmers and villagers at large. Botha et al. (2014b) mentioned that the "blaming and dependence syndromes" and lack of communication among the parties involved is hampering development. There is no agricultural organisation in the village to assist farmers or villagers with agricultural production and advice.

Recently, the newly allocated extension officer, when realising the challenges faced by livestock farmers, especially sheep farmers, established wool growers' associations. The associations started with only five people; but after three-and-a-half years, all the sheep owners (more than 21) have joined the associations when they realised the importance and benefits of such an association. Eventually, with the efforts of the extension officer, a wool machine was donated to the farmers. The extension officer provided wool classification training to the farmers and, once the wool has been classed, it is packed and transported to BKB in King William's Town, where it is sold on behalf of the farmers.

## 4.6 GOVERNMENTAL DEPARTMENTS OR STRUCTURES, INCLUDING MUNICIPALITIES

A number of government departments are directly involved in providing services in both villages (Table 4.3). Some of those departments are not meeting their obligations and/or duties. One such department is the Department of Health, which is supposed to provide the villagers with anything related to medical assistance. Both villages have one clinic each. Unfortunately, these clinics have a shortage of chronic medication. The medical team at each clinic comprises three nurses, two assistant nurses, a cleaner and a volunteer. From June 2015 until the time of reporting, a doctor (general practitioner) visited the clinics once a week (on Mondays).

**Table 4.3: List of governmental departments within the Krwakrwa and Upper Ncera villages and their functions**

| Government departments | Function or purpose | Meet their responsibilities or not |
|---|---|---|
| Raymond Mhlaba Local Municipality | Electricity delivery, water for household use, sewage and sanitation, stormwater systems, refuse removal, firefighting services, municipal health services, decisions around land use, municipal roads, municipal public transport, street trading, fresh food markets, parks and recreational areas, libraries and other facilities, and local tourism. | • Not even a single reconstruction and development programme (RDP) house has been built in either of the two villages.<br>• Despite clear policies, there is still a serious problem with regard to issues of land and power between the tribal leadership and the municipality.<br>• Taps run dry for a long period without any explanation from the municipality.<br>• Roads are in a poor condition.<br>• Refuge is not collected.<br>• Recently ventilated pit-latrine toilets were built, but it was of |

| Government departments | Function or purpose | Meet their responsibilities or not |
|---|---|---|
| | | poor quality and some broke during rainy days.<br>• In general, the municipality provides substandard services to the rural people who reside in these villages. |
| Department of Rural Development and Agrarian Reform | Creates vibrant, equitable, sustainable rural communities and food security for all. | • Encourages villagers, especially smallholder farmers, to produce efficiently.<br>• Has failed to assist smallholder farmers to successfully utilise their croplands, has a negative effect on their nutrition, development and success. |
| Department of Cooperative Governance and Traditional Affairs | Improves cooperative governance across the three spheres of government, in partnership with institutions of traditional leadership, to ensure that provinces and municipalities carry out their service delivery and development functions effectively. | • Its failure to resolve conflict between the municipality and traditional leaders is a great concern. It affects service delivery to the people. |
| Department of Education | Ensures that the education sector assesses the quality of teaching and learning, and provides remedial action in identified areas to improve learning outcomes in numeracy and literacy. | • Despite the village having two schools (primary and secondary), bad situations that are being experienced at the high school have a negative impact on the learners at large since the Department fails to provide solutions. A shortage of teachers is also a great concern. |
| Department of Health | Improves the health status through the prevention of illness, disease and the promotion of healthy lifestyles, and consistently improves the health care delivery system by focusing on access, equity, efficiency, quality and sustainability. | • The shortage of medication at the clinics and the availability of ambulances on time is a serious threat to the lives of the people. |
| South African Police Service | Prevents, combats and investigates crime, maintains public order, protects and secures the inhabitants of South Africa and their property, upholds the Constitution and enforces the law. | • Non-visibility within rural areas allows criminals to roam the streets freely.<br>• Failure to address cases (especially stock theft) poses a serious threat to the wellbeing of the villagers (smallholder farmers in particular). |
| Department of Social Development | Management and oversight over social security, encompassing social assistance and social insurance policies that aim to prevent and alleviate poverty in the event of life cycle risks, such as loss of income | • Provides social grants.<br>• Budget cuts in supporting the old age centres in both villages puts the lives of the elderly people in jeopardy. |

| Government departments | Function or purpose | Meet their responsibilities or not |
|---|---|---|
| | due to unemployment, disability, old age or death occurring.<br><br>Developmental social welfare services that provide support to reduce poverty, vulnerability and the impact of human immunodeficiency virus (HIV) and acquired immunodeficiency syndrome (AIDS) through sustainable development programmes in partnership with implementing agents such as state-funded institutions, NGOs, CBOs and faith-based organisations. | |

## 4.7 EXTENSION SERVICES AND THE ROLE THEY PLAY

Agricultural extension programmes have been one of the main channels of addressing rural poverty and food insecurity (Danso-Abbeam et al., 2018). This is because they have the means to transfer technology, support rural adult learning, assist farmers in problem-solving and getting farmers actively involved in the agricultural knowledge and information systems (Christoplos and Kidd, 2000). According to the Food and Agriculture Organisation (FAO) (2010), the extension service should facilitate the access of farmers, their organisations and other market actors to knowledge, information and technologies, facilitate their interaction with partners in research, education, agribusiness and other relevant institutions, and assist them to develop their own technical, organisational and management skills and practices. Alemu et al. (2016) mentioned that extension service providers make an innovation known to farm households, act as a catalyst to speed up the adoption rate, control change and attempt to prevent some individuals in the system from discontinuing the diffusion process.

By definition, extension is deemed a primary tool for making agriculture, its related activities and other economic activities more effective and efficient to meet the needs of the people (Danso-Abbeam et al., 2018). Danso-Abbeam et al. (2018) further mention that it is therefore regarded as a policy tool to promote the safety and quality of agricultural products. Agricultural extension is aimed primarily at improving the knowledge of farmers for rural development. As such, it has been recognised as a critical component for technology transfer. Thus, agricultural extension is a major component to facilitate development, since it plays a starring role in agricultural and rural development efforts (Bonye et al., 2012).

Agricultural productivity in the study areas has declined drastically over the years. Most croplands have not been used for over 20 years. This decline can be linked to various problems, such as labour migration to cities with the aim of seeking job opportunities, the lack of agricultural equipment in rural areas and inadequate support from government. Once the project was introduced to the smallholder farmers, it assisted in vegetable and crop production, thereby promoting food security for these communities. Local extension officers were involved as a link between the project and the local smallholder farmers.

Their involvement included organising and attending meetings, participating in surveys or data collection, attending trial demonstrations and monitoring farmers' progress. The extension officer's contribution changed the scope of the project completely, as she made sure that the smallholder farmers and villagers, in general, realised the importance of the project and their own success by engaging with them.

**Table 4.4: A comparison of the accessibility of extension services before and after the project intervention**

| Received visit or valuable assistance from extension officers | Before | | After | |
|---|---|---|---|---|
| | **Krwakrwa** (%) n = 100 | **Upper Ncera** (%) n = 63 | **Krwakrwa** (%) n = 100 | **Upper Ncera** (%) n = 63 |
| Yes | 47 | 49 | 96 | 95 |
| No | 53 | 51 | 4 | 5 |

As mentioned previously, there were many challenges at the beginning of the project. Smallholder farmers were not working together or grazing their livestock together in one place (those who have livestock). There were no camping systems or fences to demarcate rangelands so that palatable grasses could be available for the better part of the year. At the beginning, smallholder farmers from both villages (53% in Krwakrwa and 51% in Upper Ncera) said that they struggled to access extension services, but since the intervention by the project team, the availability and accessibility of the extension officer to the farmers improved drastically and made significant changes. Of the smallholder farmers in Krwakrwa and Upper Ncera, 96% and 95%, respectively, mentioned that they now have access to an extension officer, and have had a number of consultations. They further mentioned that the advice and time the extension officer has for them have improved their perception and agricultural activeness. The hard work of the extension officer clearly displays the fact that, when all teams (extension and smallholder farmers) have common goals, act and work together, more can be achieved beyond anyone's imagination. Therefore, the efficiency of agricultural extension work depends on the availability of extension professionals who are skilled, inspired, dedicated and quick to respond to the ever-changing social, economic and political environment (Ayele et al., 2003).

## 4.8 SUMMARY

The introduction of institutional arrangements within the two villages was seen as a critical factor that will assist in guiding and eradicating conflict. Various scientists emphasised the fact that institutions and institutional arrangements are vital for the development of the agricultural sector within the rural areas. Therefore, functional and workable institutional arrangements were seen as yardsticks that will play a pivotal role in their development. In that regard, various materials and methods were implemented with the aim of understanding and capturing those institutional arrangements that existed, or had ceased to exist in the selected villages. At a later stage, when the data was captured, it was analysed and shared with all relevant stakeholders, including the beneficiaries, for conclusion, adoption and implementation.

The smallholder farmers bought into the idea and made a commitment. Their involvement started through the investigation of institutional arrangements in the two villages to the level where they had to adopt those that were suggested and introduced to them. The critical roles played by all made it possible for the team to succeed in investigating, advising and reaching a conclusion that could be adopted and implemented. Its monitoring involved everyone, including the committee that was selected by the smallholder farmers. The committee was tasked to make sure that everyone adhered to the institutional arrangements, whether they were involved in agricultural production or not.

Various M&E steps were adopted. Monitoring was done on a quarterly basis to give farmers enough time to adopt and implement the arrangements successfully. The aim was to make sure and assess whether the smallholder farmers had adopted the institutional arrangements and put them into practice. Not only was the focus on adoption, implementation and monitoring, but the strengths, weaknesses, opportunities and threats were also examined. Their impact was assessed and changes made where necessary.

On the other hand, the role and involvement of the traditional leadership was examined and assessed. Their involvement made things run smoothly, despite challenges from those who do not recognise the authority of the traditional leadership. Despite their political affiliations or feelings regarding traditional leaders, villagers still have to abide by the law. The involvement of headmen and the selected committee played a critical role in ensuring that cases that were brought to them were resolved within a short period of time.

The monitoring process was followed by an assessments of the different private (village-based association or cooperatives) and government departments, including the municipality. The majority of the village-based organisations were found to have failed the farmers. Only the wool growers' association was found to be effective and working hard to achieve what was best for its members. The failure of some corporations or associations put the smallholder farmers and/or villagers a few years back. Government departments were discovered to be failing at their mandates. The shortage of chronic medication at the clinic was a serious issue as it affects the lives of those who are ill or sick. In terms of security, the poor visibility of the police and stock theft cases that have been dragging for a long time had a negative impact on the success of the smallholder farmers and the control of crime in the area. That led to most of the farmers not opening cases or reporting theft to the police because all their cases remained unresolved for years until the police closed the cases without any explanation. Poor roads impact negatively on production and transportation costs for smallholder farmers. All the roads entering or leaving the two villages are gravel roads, which makes them impossible to drive on during the rainy season. CBOs had collapsed due to a lack of trust and unfaithfulness, since money was unaccounted for, and that led to people losing faith in them.

The new extension officer who was assigned to the villages brought a whole new perspective to the lives of the smallholder farmers. This person is very hand-on and works closely with the farmers. In less than four years, a fully functional wool growers' association was established with the aim of helping the farmers sell their wool on the market with better prices than before.

# CHAPTER 5: EVALUATION OF APPROPRIATE RAINWATER HARVESTING AND CONSERVATION TECHNOLOGIES FOR INCREASED CROP PRODUCTION

The objective of this chapter is to assess the selected RWH&C technique in combination with sound management practices and bio-slurry application for improved homestead and cropland productivity in communal areas through on-station and on-farm research. On-station field experiments were carried out to compare IRWH with various management practices with various bio-slurry application rates and to test their applicability. On-farm studies consisted of demonstration plots in the homestead gardens of selected beneficiaries in Krwakrwa and Upper Ncera where roof water harvesting, IRWH with bio-slurry as a fertilizer source and biogas production as a renewable energy source were used.

This chapter covers three distinct topics: roof water harvesting, homestead production and cropland production. Although the scope might seem wide, it has a common goal. All these “production areas” can be utilised for food production and, ultimately, contribute to household food security. Rainwater collected from rooftops in tanks can be used for domestic purposes and for the supplemental irrigation of crops grown in homestead gardens. Water collected in tanks can also be mixed with cattle manure to feed the bio-digesters for biogas production. In addition, the effluent from the bio-digesters is used as an organic fertilizer for food production in the homestead gardens. The homestead garden provides an ideal opportunity for food production, especially vegetable production. This can provide villagers access to a more nutritional diet by producing a variety of vegetable crops in the homestead gardens. Where RWH&C technologies, especially IRWH, are used in the homestead gardens, the production of vegetables throughout the year is made possible. However, if community members want to eradicate hunger and poverty completely in their communities, they will have to expand their production to the unutilised communal croplands. Low yield or total crop failure is common in the rural areas of the Eastern Cape, but by employing suitable RWH&C technologies in the communal croplands, sustainable production becomes possible.

## 5.1 WATER QUALITY OF DOMESTIC RAINWATER HARVESTING

### 5.1.1 Introduction

Domestic rainwater harvesting can be defined as the collection of rainwater that has run off from ground or rooftop surfaces and is used as a domestic water supply for drinking, cooking and washing (Worm and Hattum, 2006). For this study, the water was also used to give crops in the homestead gardens supplementary irrigation during periods of drought and to feed the bio-digesters for biogas production.

There are a number of advantages for the collection and storage of rainwater for domestic use:

- It is a simple, low-cost technology that makes use of inexpensive material to store rainwater.
- In rural areas, in particular, water sources are traditionally situated a distance away from the village, and domestic rainwater harvesting provides point-of-use for added convenience.
- Rainwater is a renewable resource with a low impact on the environment.
- Rainwater may be used as a supplementary water resource along with more “conventional” water-supply technologies to balance existing water supplies in rural communities and even in areas of the world where adequate water resources are available to combat ever-growing water demands.

For domestic use, RWH can be applied advantageously under the following scenarios, according to the African Development Bank (2008):

- Conventional water supply systems based on boreholes (groundwater) or perennial surface water sources are not always technically feasible. This will typically be in areas with insufficient or even no yields from groundwater wells, no or limited perennial rivers or other surface water bodies, and cases where available water resources have been polluted.
- Groundwater-based water supply systems (e.g. hand pumps) could be vulnerable to seasonal fluctuations of the groundwater level, and RWH structures could be a complementary or security water supply.
- Groundwater might be problematic quality-wise (fluoride, arsenic, hardness, salinity, etc.) and no easily accessible surface water resource is available.
- Conventional water supply systems might be technically possible, but for socio-economic reasons, unattractive. This could be villages on hill tops (where a conventional water system would include pumping machinery and thereby complicated and expensive operations that require maintenance) or remotely located villages with limited households, where the provision of a regular piped water supply can only be achieved at an unreasonably high cost (long supply pipelines).

Rainwater in rural areas is usually safe to drink unless it has been contaminated or stored improperly. Rainwater can be contaminated by the following:

- Bird and other small animal droppings (e.g. lizards, mice and frogs)
- Other debris, including dead animals and insects that contain microscopic organisms
- Air pollution from any nearby industrial emissions or heavy road traffic
- Industrial or agricultural activities that generate dust and pesticide spray drift
- Smoke or other emissions from veld fires or fires for cooking
- Storage in a water tank or pipework that is not clean

Collecting water from roofs for household and garden use is widely practised across South Africa. Tanks and containers of all types, from large brick reservoirs to makeshift drums and buckets, are a common sight in rural areas. Roof water harvesting has three main components: the roof, the gutter and the storage tank.

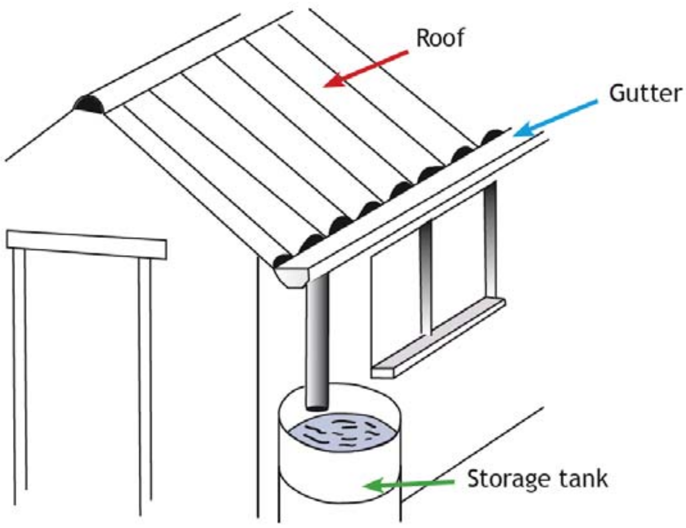



**Figure 5.1: Diagrammatic representation of a roof water harvesting system**

The advantages of collecting water from roofs are as follows:

- Roofs are physically in place and runoff is immediately accessible.
- Water collected from roofs is much cleaner than from land runoff.
- Most of the rainwater falling on the roof can be collected, as there is little absorption or infiltration on the roof surface.

### 5.1.2 Domestic rainwater harvesting in South Africa

The Department of Water Affairs and Sanitation aims to provide all South African citizens with access to basic water and sanitation services. The Department has recommended the provision of potable water to rural communities as a priority to achieve this goal. Rainwater harvesting has been earmarked as a short-term intervention to provide water, especially to dispersed settlement areas (Department of Water Affairs, 2009). In the 2011/12 financial year, the Department of Water Affairs installed 8,068 RWH tanks in eight provinces. Of these tanks, 6,308 were installed to provide access to a water supply and 1,760 were installed for food production (Department of Water Affairs, 2012).

Domestic RWH has the potential to improve water availability in rural communities in southern Africa with 55,000 households utilising a rainwater tank on-site as their main source for drinking water in South Africa in 2010 (Dobrowski et al., 2014). Rainwater harvesting could also provide water for small-scale, home-based productive activities, such as vegetable gardening, which could make a positive contribution to food security for people from lower socio-economic groups.

The general perception of South Africans is that water from a rainwater tank in the yard and a water carrier or tanker is safe, clean, tastes good and does not have a bad smell. It seems as if households perceive water from a well and a spring to be safer, cleaner, better tasting and free of bad smells when compared to water from a stream or river and stagnant water from a dam or pool. Of the water that is from an unimproved source, stagnant water from a dam or pool was the one considered to be of a poor quality (Stats SA, 2016).

In 2015, RWH tanks on site in South Africa only contributed 0.7% of the main source of drinking water used by households.

**Table 5.1: Statistics on rainwater tanks as the main source of drinking water used by households, 2002–2015 (Stats SA, 2016)**

| Year | 2002 | 2004 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number | 60 | 38 | 49 | 61 | 68 | 44 | 45 | 91 | 82 | 74 | 68 | 120 |
| Percentage | 0.6 | 0.3 | 0.4 | 0.5 | 0.5 | 0.3 | 0.3 | 0.6 | 0.6 | 0.5 | 0.4 | 0.7 |

Duncker and Matsebe (2014) indicate that, for South African conditions, it is necessary to investigate and quantify the following parameters for rainwater tanks:

- Wind carrying pollutants and contaminants
- Birds, animals and insects on the roof
- Dust, debris, paint and rust
- Chemical contaminants (heavy metal fall-out, pesticide, nitrates and sulphates)
- Environmental contaminants (acid rain, ocean)
- Microbial contaminants that may affect water quality (E coli, protozoa, viruses, water-borne pathogens)
- Vector contaminants such as mosquitos

### 5.1.3 Material and methods

With roof water harvesting, rainwater is harvested from rooftops and stored in above-ground JoJo water tanks. This was implemented and demonstrated at the homesteads of the selected beneficiaries in Krwakrwa and Upper Ncera where the bio-digesters were constructed and IRWH techniques demonstrated for household food production. This harvested rainwater was mainly used for the following:

- Biogas production, where cattle manure was mixed with water to feed the bio-digester
- Supplemental irrigation for crop production in the homestead garden
- Domestic purposes (cooking, drinking and washing)

Before biogas production could be integrated into the farming system of the rural households, it was necessary to determine whether it would be possible to harvest sufficient water to fill the bio-digester throughout the year. Long-term weather data from Alice, about 8 km from Krwakrwa, was used to get an indication of the rainfall potential. The size and design of the rainwater collection system depended on how much water was required, the expected rainfall and the amount of untreated water that needed to be stored. Where a villager was responsible for the installation of their own tank, the size of the tank was further determined by the financial situation of the individual's household.

Villagers were provided with data sheets to keep accurate records of the rainfall, volume of water collected from the roofs and the volume of water used for various applications (Figure 5.2). Each beneficiary also received a hand rain gauge to measure the rainfall.

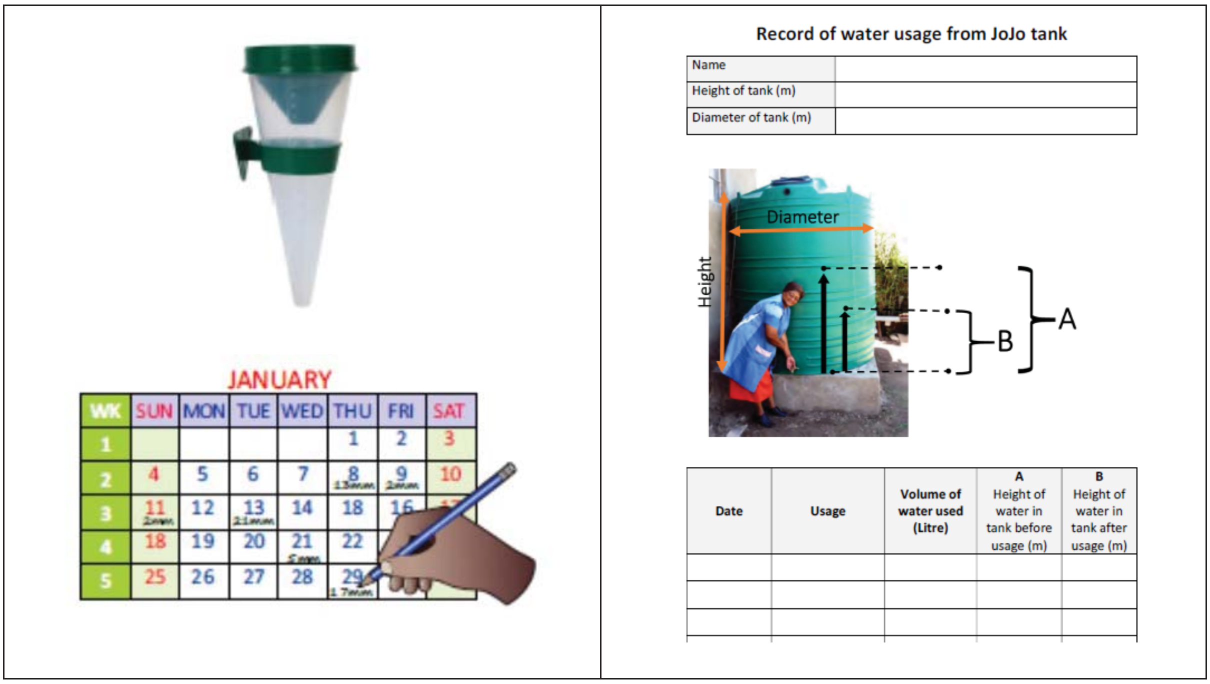



**Figure 5.2: Record keeping of rainfall and water collection and use of collected water**

Municipal taps often ran dry for long periods, so villagers used hosepipes to fill up their tanks whenever tap water was available. The volume of water in the tanks was therefore not a true reflection of the volume of water collected from the rooftops. Households were then identified where the water in the tanks was a mixture of tap water and water collected from the rooftops, and households where no tap water was added. Chemical analysis of the collected samples was done at the laboratory of the ARC-SCW to determine its suitability for use in the bio-digesters, supplementary irrigation in the homestead gardens and household consumption.

The water samples were taken at selected homesteads in Krwakrwa and Upper Ncera. The dwellings at each homestead consist of a number of thatched rondawels and a house with a corrugated iron roof. However, in order to do roof water harvesting, gutters were fitted to the houses with corrugated iron roofs to ensure maximum water collection. The water samples were separated into only rainwater collected from the rooftop and where the water in the tank was a mixture of tap water and collected rainwater. The sampling of the harvested water was taken during the rainy season (February) and the drier winter period (May). Twelve water samples were collected directly from the plastic storage tanks. The tanks were installed above ground and samples were taken from the tap connected to the JoJo tank. Water samples were analysed for water quality parameters, including turbidity, electrical conductivity, pH, sulphates ($SO_4^{2-}$), phosphates ($PO_4^{3}$), nitrates ($NO_3^-$), boron, magnesium, sodium, potassium, calcium, sodium bicarbonate, alkalinity and temporary hardness. The analyses were done at the laboratories of the ARC-SCW.

Rainwater harvesting data by Selalai et al. (2018) from another rural area in KwaZulu-Natal was also included for comparison with the data from Krwakrwa and Upper Ncera.

### 5.1.4 Results and discussion

The water analyses (Table 5.2) are characterised by very low concentrations of the chemical parameters analysed. It was therefore not possible to make meaningful distinctions between water collected from roofs only and a mixture of rooftop and tap water. From a chemical perspective, all the water samples are well below the threshold value for domestic use, and therefore safe to drink, according to the South African Water Quality Guidelines for Domestic Use (DWAF, 1996a). All the water samples are Irrigation Class I Water (DWAF, 1996b), and even very salt-sensitive crops can be grown with the water. The water is, however, not in chemical equilibrium and it would be corrosive. The water may necessitate the premature replacement of pipes, irrigation canals and other irrigation equipment.

**Table 5.2: Water analyses of selected parameters for water collected from rooftops and a mixture of rooftop and tap water**

| Sample No | Date taken | Source | pH | EC (mS $m^{-1}$) | $NO_3$ (mg $ℓ^{-1}$) | Cl (mg $ℓ^{-1}$) | Na (mg $ℓ^{-1}$) | Ca (mg $ℓ^{-1}$) | Mg (mg $ℓ^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| 1. | 2020-02-27 | Roof | 6.47 | 2.4 | 2.35 | 1.83 | 0.21 | 1.80 | 0.05 |
| 2. | 2020-02-27 | Roof | 6.39 | 2.4 | 2.38 | 1.89 | 0.15 | 1.80 | 0.00 |
| 3. | 2020-02-27 | Roof | 6.41 | 3.6 | 3.60 | 2.50 | 0.42 | 4.41 | 0.08 |
| 4. | 2020-02-27 | Roof | 6.79 | 8.6 | 1.56 | 9.55 | 5.71 | 6.18 | 0.24 |
| 5. | 2020-02-27 | Roof and tap | 6.87 | 2.3 | 1.34 | 2.28 | 0.41 | 1.58 | 0.16 |
| 6. | 2020-05-21 | Roof and tap | 6.70 | 2.1 | 1.17 | 2.43 | 0.38 | 1.08 | 0.08 |
| 7. | 2020-05-21 | Roof | 6.58 | 2.1 | 1.56 | 1.58 | 0.12 | 1.48 | 0.00 |
| 8. | 2020-05-21 | Roof | 6.55 | 2.6 | 2.00 | 1.75 | 0.09 | 3.03 | 0.02 |
| 9. | 2020-05-19 | Roof and tap | 6.70 | 3.8 | 1.77 | 2.41 | 0.55 | 5.48 | 0.43 |
| 10. | 2020-05-21 | Roof | 6.76 | 5.8 | 1.76 | 6.50 | 3.7 | 3.80 | 1.74 |
| 11. | 2020-05-21 | Roof | 6.77 | 3.5 | 1.56 | 2.05 | 0.56 | 5.57 | 0.44 |
| 12. | 2020-05-19 | Roof | 6.81 | 2.7 | 2.12 | 2.52 | 0.69 | 1.37 | 0.51 |

Nitrate ($NO_3^-$) is one of the main water chemical indicators of pollution. The highest nitrate concentration of 3.6 mg $\ell^{-1}$ (Sample 3) is well below the threshold value of 44 mg $\ell^{-1}$ for domestic use (Table 5.2). It is, however, dangerous to indicate that the water was not contaminated, because no microbiological analyses were done. Dobrowksy et al. (2014) indicate, in their Kleinmond study, that while the chemical quality of the rainwater was generally within the stipulated drinking water guidelines, the results obtained for microbial analysis often significantly exceeded ($P < 0.05$) the microbial guideline standards. The water from the RWH tanks in Kleinmond was not fit for human consumption and treatment was required before the water source could be used for drinking. This highlights the fact that microbial analyses are critical and must be done before any recommendation can be made, especially for domestic use.

The very low values for the basic chemical parameters (Table 5.2) correspond mostly with the low values found in the Bergville study (Table 5.3) done by Selalai et al. (2018). It is important to note that high heavy metal contamination is possible, especially from metallic roofs, according to Selalai et al. (2018), but this was not analysed in this study.

**Table 5.3: Selected physical and chemical characteristics of water collected from various sources (after Selalai et al., 2018)**

| | Roof | | | Yard | Dam | Well | WHO | t-test |
|---|---|---|---|---|---|---|---|---|
| | Metallic | Thatch | Tile | | | | | |
| n | 35 | 1 | 2 | 42 | 1 | 1 | | |
| Turbidity (NTU) | 0.11 (0.03–1.08) | 0.04 | 0.13 | 0.11 (0.3–0.68) | 0.04 | 0.03 | 5 | NS |
| EC (µS $cm^{-1}$) | 15.5 (8.30–49.1) | 18 | 15.4 | 65 (36.6–127.4) | 61.9 | 20.4 | NA | S |
| pH | 6.66 (6.30–7.49) | 6.3 | 6.7 | 6.9 (6.3–7.1) | 6.4 | 6.7 | NA | S |
| Al (mg $\ell^{-1}$) | 0.17 (0–2.56) | 0.07 | 0.17 | 1.53 (0–8.3) | <DL† | 0.01 | 0.1 | S |
| As (mg $\ell^{-1}$) | 0.04 (0–1.01) | <DL† | 0.04 | 0.01 (0–0.04) | 0.01 | 0.01 | 0.01 | S |
| B (mg $\ell^{-1}$) | 0.08 (0–1.10) | 0.07 | 0.08 | 0.02 (0–0.26) | 0.02 | 0.01 | 0.7 | S |
| Ca (mg $\ell^{-1}$) | 2.03 (0.1–9.30) | 1.08 | 2.06 | 9.6 (0.1–29.8) | 8.35 | 1.67 | 500 | S |
| Cd (mg $\ell^{-1}$) | 0.04 (0–1.02) | <DL† | 0.03 | 0.001 (0–0.03) | <DL† | <DL† | 0.003 | S |
| Cr (mg $\ell^{-1}$) | 0.03 (0–1.00) | <DL† | 0.03 | 0.002 (0–0.03) | <DL† | <DL† | 0.05 | S |
| Cu (mg $\ell^{-1}$) | 0.02 (0–0.90) | <DL† | 0 | 0 (0–0.13) | <DL† | <DL† | 2 | S |
| DOC (mg $\ell^{-1}$) | 0.35 (0–5.71) | 4 | 0.3 | 2.06 (0–10.03) | 1.12 | <DL† | NA | S |
| Fe (mg $\ell^{-1}$) | 0.13 (0–1.25) | 0.08 | 0.13 | 1.29 (0–4.56) | 0.1 | 0.03 | NA | S |
| K (mg $\ell^{-1}$) | 0.10 (0.01–1.05) | 0.38 | 0.1 | 0.9 (0.01–2.7) | 0.16 | 0.09 | NA | S |
| Mg (mg $\ell^{-1}$) | 0.28 (0–1.38) | 0.45 | 0.28 | 1.3 (0.05–6.2) | 5.35 | 0.91 | NA | S |
| Mn (mg $\ell^{-1}$) | 0.021 (0–0.87) | <DL† | 0 | 0.018 (0–0.20) | <DL† | <DL† | 0.1 | NS |
| Na (mg $\ell^{-1}$) | 0.45 (0.1–3.05) | 0.37 | 0.46 | 4.25 (0.05–10.07) | 4.05 | 2.59 | NA | S |
| Ni (mg $\ell^{-1}$) | 0.03 (0–1.00) | 0.001 | 0.03 | 0.00 (0–0.03) | <DL† | <DL† | 0.07 | S |
| $NO_3^-$ (mg $\ell^{-1}$) | 1.70 (1.0–4.60) | 1.4 | 1.7 | 2.73 (1.1–4.5) | 0.6 | 1.7 | 50 | NS |
| Pb (mg $\ell^{-1}$) | 0.02 (0–0.86) | <DL† | 0 | <DL† | <DL† | <DL† | 0.01 | S |
| $Po_4^{-3}$ (mg $\ell^{-1}$) | 0.28 (0.2–0.43) | 0.41 | 0 | 0.31 (0.19–0.77) | 0.26 | 0.3 | NA | NS |
| Se (mg $\ell^{-1}$) | 0.02 (0–0.82) | <DL† | 0 | <DL† | <DL† | <DL† | 0.04 | S |
| $SO_4^{-2}$ (mg $\ell^{-1}$) | 0.30 (0.25–0.38) | 0.38 | 0 | 0.43 (0.3–1.9) | 0.28 | 0.25 | 400 | NA |
| Zn (mg $\ell^{-1}$) | 2.20 (0.01–4.57) | 0.29 | 2.17 | 1.78 (0–3.8) | 0.02 | 0.08 | NA | NS |

*75% of the samples are above the World Health Organisation (2004) limit for drinking water;*
*† < DL: Below detection limit.*

### 5.1.5 Summary

From the basic water chemical analyses done, all the water samples were suitable for domestic and irrigation use. It must be emphasised that no microbiological or heavy metal analyses were done that could have a negative effect on the safe use of the water.

Health risks associated with the consumption of harvested rainwater remain one of the major obstacles hampering the large-scale implementation of RWH systems, as microbial and chemical contaminants have previously been detected in rainwater tanks (Spinks et al., 2006; Sazakli et al., 2007; Lee et al., 2010; Ahmed et al., 2012; Huston et al., 2012). Health problems associated with poorly maintained rainwater tanks do not just come out of the tap. If mosquitoes can access the water in the tank, it can become a breeding ground for the spreading of disease.

The effects of pollution from rooftops into RWH systems need to be cleaned regularly to avoid faecal matter, in particular, being washed into the tank. Gutter mesh can help limit what ends up in the tank. It is necessary to de-sludge the tank at least every two years to remove the sediment that builds up in water tanks.

## 5.2 HOMESTEAD PRODUCTION

### 5.2.1 Introduction

The world is facing multiple challenges in the 21th century and beyond. These include, but are not limited to poverty, food insecurity, water scarcity, and new and complex challenges emerging due to global warming and climate change (Wani et al., 2009). The current world population of 7.6 billion is expected to reach 8.6 billion by 2030, 9.8 billion by 2050 and 11.2 billion by 2100 (United Nations, 2017). Numerous researchers and agricultural experts are of the opinion that smallholder farming could become a long-term, viable and sustainable option for increasing food security in South Africa and meeting the needs of the expected increase in population by 2050 and beyond.

Homestead gardens have become an important resource by which the rural poor are able to feed their families and reduce their vulnerability to hunger. They can play a crucial role in assisting with the provision of food for the expected population increase. Moreover, homestead gardens have become more than just about the production of food. Fernandez (2003) confirms the complexity of community gardens and identifies three benefits to community gardens: social, economic and environmental. Community gardens have become a “safety net” for many in rural South Africa. They provide those without formal employment with community-based employment (Brooks and Friedman, 1991; Light et al., 1996).

Parry et al. (2005) observed the following benefits of community gardens:

- Psychological wellbeing through positive aesthetic environmental changes (community gardeners gain a sense of pride and accomplishment, which, in turn, fosters feelings of self-worth and self-confidence)
- Gains from growing food independently, which include the situation where gardeners are relieved of purchasing vegetables or fruits from commercial sources, which creates a sense of self-reliance
- Opportunities that arise for disenfranchised individuals to join community group efforts as an active member and to take on leadership roles to work towards collective goals

These gardens played an important role in national food security by supplementing rations and providing essential nutrients that cannot be supplied otherwise by the food environment of the time.

Furthermore, homestead gardens have the following advantages:

- The location of the garden close to the home reduces the risk of losses from dangerous wild animals, as well as from theft.
- Species diversity and staggered planting increase the likelihood of crop survival by taking advantage of the inhibition of pests and disease build-up, as could be the case in a mono-cropping system, and spread the risk of crop failure in the case of adverse weather conditions (the problem of staggered planting is that it is often affected by seasonality, land and water availability, and most people may find it labour intensive and time-consuming to practice staggered planting, given that most people who partake in food gardening are women who also have other responsibilities).
- Homestead garden operations can readily be integrated into daily household chores, helping women to earn an income while undertaking household chores (it is, however, not clear how these women can earn an income by partaking in food gardens, since most of them do so for their own consumption).
- Homestead gardens can provide environmentally sound opportunities for waste disposal, including kitchen waste, paper and other materials because of their close proximity to homes.

Apart from the abovementioned problems, the project aimed to play a crucial role in making sure that the villagers of Krwakrwa and Upper Ncera enjoyed food security at all times. The discussions that follow are based on the work that was conducted by the project team in the villages of Krwakrwa and Upper Ncera to contribute to household food security.

### 5.2.2 Material and methods

The project team and villagers compiled selection criteria for households that would receive bio-digesters and act as demonstrators. A number of demonstration plots (three in each village) and ten homesteads that would have received biogas digesters were identified with the help of the Village Committee. Transact walks were taken to more than 40 households with the aim of assessing whether these households met the initial requirements to be provided with a biogas production system. The same procedure was followed for those households where homestead gardens were used as demonstration plots. Thereafter, an MoU was signed with the heads of the selected households, giving team members permission to enter their homestead gardens to monitor the bio-digesters and IRWH demonstration plots, as well as to agree to fully participate in the project. Villagers from Krwakrwa were assisted with the construction of IRWH basins and the planting of various vegetable crops in the selected homestead gardens.

Villagers from Upper Ncera saw the IRWH technique in the neighbouring Krwakrwa and showed a keen interest in applying it for household food production as well. The IRWH technique was then formally introduced to the villagers in Upper Ncera through the active participation of the village headman, who mobilised the villagers. Later, demonstrations were conducted on the three nominated homestead gardens (as demonstration plots), together with the villagers. Within a short period of time, the technology had expanded to a number of homestead gardens after receiving hands-on training on the construction of the IRWH structures.

### 5.2.3 Results and discussion

**Krwakrwa Village**

Since the start of the project, project team members have visited Krwakrwa numerous times. The aim of these visits was to consult with the villagers for a number of reasons, including the identification of the households that would be suitable to apply IRWH for crop production in their homestead gardens, describing the soils in the respective homestead gardens and selecting households that are suitable for the implementation of biogas production.

According to the signed agreement with the project funder, bio-digesters were to be installed at only two homesteads. Demonstrations of roof water harvesting and IRWH, for household food production, would then have taken place at only the two selected households. Villagers had to identify households that they considered worthy of receiving bio-digesters based on the selection criteria provided. The selection criteria included soil depth, soil texture, access and security of garden, size of garden, utilisation of garden, crop diversity, gardening equipment, access to water, condition and size of the roof, water storage facilities, number of cattle, kraaling facilities, dipping of animals, animal movement, access to manure, current energy source, number of able-bodied people to work in the garden and number of household members to benefit from the project.

In the end, the villagers proposed 22 households that they believed could be potential recipients of the bio-digesters. It was the task of the project team, together with the villagers, to select the two households that were to receive the bio-digesters. Project team members believed that only two bio-digesters would not make a significant impact, so decided to seek extra funding from potential funders. Based on hard work and engagement with different organizations and businesses, funding was received for an extra 12 bio-digesters. That increased the total number of bio-digesters to be installed in Krwakrwa and Upper Ncera to seven in each village. Once the selected households were announced, it was agreed that the heads of those households should sign a MoU with the project team to give the team members permission to enter their homesteads to monitor the bio-digesters and conduct IRWH trials by taking samples whenever needed.

The IRWH crop production technique was implemented and demonstrated in the homestead gardens for the production of cash crops and a variety of vegetables. This was done at the same homesteads where the roof water harvesting and biogas production were demonstrated. The IRWH technique has proven, over many years, to be a sustainable crop production technique, especially for homestead food production. The research team and extension officers assisted the villagers to make informed decisions about the crops that were planted in the homestead gardens. The effluent from the biogas digesters was applied as a liquid fertilizer for the production of crops and vegetables in the homestead gardens and/or to establish fodder banks for livestock. Villagers were not familiar with the use of bio-slurry as a fertilizer, so it took time and effort to convince the villagers of the advantage of applying bio-slurry as a fertilizer source. Villagers often neglected their bio-digesters and did not feed them regularly with a mixture of cattle manure and water. The bio-slurry then dried out and the biogas production stopped. Bio-digesters then had to be cleaned out and restarted several times. Bio-slurry was therefore not always readily available for use as a fertilizer. Villagers were also unsure of the application rate and method of application of the bio-slurry. Since technical assistants were unable to provide them with clear guidelines, they were sceptical about the use of bio-slurry. Only after the villagers had visited the on-station experimental plots at Fort Cox College during a Farmer's Day, where they saw the application of the bio-slurry and it was properly explained to them, were they more open to use this alternative fertilizer source. This has emphasised the importance of having demonstration plots, so that villagers can learn from them and apply what they see at the demonstration plots in their own homestead gardens.

Since 2016, technical assistants from the ARC-SCW have assisted the villagers to construct IRWH basins in the selected homestead gardens in Krwakrwa. At each of the selected households, the principles of IRWH were explained to the members of that household. Each household was also provided with a visual booklet on how to implement, maintain and use the IRWH technology in their homestead gardens for food production. The technical assistants demonstrated the construction of the IRWH structures, after which each household had to continue with the construction of the basins in the rest of the homestead garden under the supervision of the technical assistants. However, villagers did not fully understand the functioning of the IRWH technique and some destroyed the basins after the technical assistants left, continuing with their conventional practices.

After discussions with the villagers and explaining to them again that they would forfeit the opportunity to be part of the RWH and biogas production initiative if they fail to adhere to the contractual agreements stipulated in the MoU, they agreed to reconstruct the basins. For the duration of the project, villagers were visited regularly to provide then with much needed advice and assistance with the maintenance of their homestead gardens. The villagers were empowered in the use of these technologies at various events, such as group training sessions, workshops and farmers' days (Appendix 10). They received training on all aspects of the value chain, from production to marketing. Training topics included the construction and maintenance of IRWH basins, the planting of vegetables, weed and pest control, harvesting and processing, record-keeping, marketing and the role and function of the committees.

Most villagers did not have money to buy either seeds or seedlings, and some of the gardens where basins were constructed were neglected and taken over by weeds. Along the way, some lost interest in utilising the IRWH technique for crop production. Several meetings had to be conducted with villagers to address the problem of poor participation in the application of IRWH in their homestead gardens. Once villagers had renewed their commitment to actively participate in the project, the IRWH technique was expanded to more homestead gardens for household food production.

Just as was the case with the roof water harvesting, villagers received data sheets to keep record of their inputs and produce from their homestead gardens. The record-keeping was extremely poor, since villagers did not realize the importance of accurate record-keeping. This is a problem experienced in many rural communities where new technologies are implemented. If villagers keep records of their inputs and produce, they will soon see how they have benefitted from using the new technologies. They will not only see how much more they have harvested by making use of the new technologies, but will see how much they have actually saved or earned from eating food produced in their own gardens or selling surpluses.

***Selection of beneficiaries***

***Signing of MoU***

***Construction of IRWH basins***

***Training of villagers***

***Meeting with villagers***

***Farmers' day***

**Figure 5.3: Project activities at Krwakrwa village**

**Upper Ncera Village**

Villagers from Krwakrwa's neighboring village, Upper Ncera, showed a keen interest in the use of the IRWH crop production technique. Some of the villagers from Upper Ncera had regularly visited Krwakrwa to familiarize themselves with this technique, and requested the technical assistants to also come to their village to demonstrate the technique there. Since the project had to be expanded to a second village, the project team decided that it would be a good idea to include Upper Ncera in the project as its villagers were eager to also apply the IRWH and biogas production technologies.

At the beginning of September 2017, villagers from Upper Ncera cleaned and fenced a community garden where the IRWH crop production technique could be implemented and demonstrated. The idea was that the villagers could work together in the garden, but as time went by, conflict started among the villagers as not all shared the workload equally. An inability to resolve conflict and work harmoniously together resulted in the collapse of the community garden, since no one took responsibility for looking after it. It ended up being full of weeds, and stray animals entered the area and destroyed all the crops that had been planted. Here the importance of functional institutional arrangements came into play to govern the working arrangements in a community garden. Collective production in a community garden is a noble idea, but the enforcement of rules ensuring that everyone plays their part is problematic. Production in homestead gardens was a more viable option, where individuals took responsibility for their own production and performance. In the homestead gardens, villagers have better control over their production, as they are not dependent on someone else's active participation.

The same training that was given to the Krwakrwa villagers was also given to the villagers in Upper Ncera. As a new and second village that was added to the project at a late stage, the same trend was followed in terms of implementation. Initially, the project in the village started with only three homestead gardens, but gradually exceeded the expectations of the project team in terms of adoption rate. One of the reasons for the rapid adoption rate might be that Upper Ncera neighbours Krwakrwa and the villagers had a good idea of what was expected of them, or their interest was based on their love of agriculture and improving their livelihoods. Unemployment within the village was very high, therefore some of the villagers rely heavily on agricultural production for their own consumption or selling produce to earn an income.

As in the case of Krwakrwa, the villagers were optimistic, but sceptical that the use of RWH&C technologies in their homestead gardens could ensure household food security. Since most of the residents in the village depended on some kind of grant as a source of income, they had stopped utilising their gardens a long time ago.

Villagers were then waiting each month to receive their grant money so that they could go to Alice to buy vegetables, either from the street vendors or from the supermarket. Instead of saving their money to buy inputs to produce their own food, they used their money to buy food. However, with their limited funds, they had a limitation on the quantity and quality of vegetables they could buy. Although not measured, it is obvious that they could not have met the required daily nutritional intake. It was also not possible to buy other food sources such as meat, dairy products, eggs and other ingredients to prepare a nutritious meal on a daily basis for their families. They did not have money to buy other household essentials either.

With the introduction of the RWH&C technologies for food production in the homestead gardens, there has been a marked improvement in food intake and household expenditure. Although the majority of the household heads were elderly women, they managed to master the IRWH technique for food production in their homestead gardens. With basic garden tools (a spade and a rake) and a positive working attitude, they were able to construct IRWH basins and maintain their gardens. The elderly were even assisted by their grandchildren to construct the basins and to weed the gardens. Since it is such a simple technique, both young and old quickly grasped the principles of the technique. As early as during the first year, households were able to create their own water-harvesting structures and plant seedlings under the watchful eye of the technical assistants. Thereafter, they were able to continue on their own without much guidance and assistance. Although the project provided seeds and seedlings to the beneficiaries, some started to buy their own inputs from an early stage. This was partly due to the fact that the project team had informed the beneficiaries from the start that they should not expect free hand-outs all the time and the project did not want to nourish a dependency syndrome.

A number of households were able to produce more than what was needed for household consumption. Surpluses were sold to fellow villages and some were even blessed enough to donate it to the church and school-feeding programme. Income generated could then be used to buy their own inputs and other household consumables. Villagers have benefitted from making use of the RWH&C technologies for food production and were generally better off than before.

### 5.2.4 Summary

It was important for the project to assist villagers with the implementation of suitable technologies that could assist them to become household food secure. To make this a reality, it was necessary to engage with all the relevant stakeholders that could contribute to improved production in the homestead gardens. The adoption of the techniques started slowly, but gradually picked up as villagers started to realise the benefits of the technologies that were introduced to them. The enthusiasm cooled down when bio-digesters were not installed quickly enough to meet the villagers' expectations. However, some individual households realised that they could still produce a variety of vegetable crops for household consumption, although they were still waiting patiently for the bio-digesters to produce sufficient effluent to be used as fertilizer in their homestead gardens.

Homestead production continued throughout the year as villagers were able to provide supplemental irrigation from water collected in the tanks. Normally, villagers struggle with food supply during the winter period, but combining IRWH with supplemental irrigation from water collected in the tanks made it possible for them to become food secure, even during the dry winter period. A point of concern was the dependency syndrome, where villagers waited for seedlings and seeds that were planted. Homestead gardens were full of weeds most of the time and not well maintained. This was a clear indication that not all the villagers understood the basic fundamental principles of crop production. If they had a better understanding of it, they would have known that the weeds compete with the crops for the available water and nutrients, resulting in lower yields. Therefore, even if they have used IRWH and bio-slurry as a fertilizer, they have not necessarily enjoyed improved production. Villagers are then often quick to claim that these technologies are not better than the conventional methods of crop production that they have been using for decades, not realising that poor weed control, for example, is the underlying reason for the poor performance.

This further highlighted the importance of effective extension services, so that villagers can be made aware of the factors that have an impact on production. Not all villagers come from an agricultural background, so they need to be educated on the fundamentals of food production. Only when they have a proper understanding of that will they be able to fully utilise the new technologies to their advantage.

Despite all the problems experienced, the establishment of homestead gardens in the two villages contributed to improved food production and rural livelihoods. The production of a variety of vegetable crops not only improved the villagers' nutritional health status, but also had a positive effect on the social environment.

## 5.3 CROPLAND PRODUCTION

### 5.3.1 Introduction

Maize production in rural areas of the Eastern Cape is very low with yields of less than 0.5 t $ha^{-1}$ (Bembridge, 1984; Anderson and Galt, 1998). There are various reasons for these low yields, including low rainfall and poor soil fertility (Fanadzo et al., 2010). This is compounded by the excessive costs of chemical fertilizers, which leads to little or no application of inorganic fertilizers. Strategies aimed at improving soil fertility should therefore consider alternatives to chemical fertilizers (Mupangwa et al., 2007).

To improve the productivity of rainfall under rain-fed production in the Eastern Cape, soil management options such as the use of maize residue and cover crop mulch can help retain soil moisture and subsequently contributes to increasing maize yield. Mulching is known to reduce evaporation from the soil surface and overall evapotranspiration, leading to improved water use efficiency (Mupangwa et al., 2007). Another advantage of using organic mulch is the addition of humus to the soil after the mulch has decomposed. This addition of humus normally results in increased soil water-holding capacity (McMillen, 2013). Furthermore, water runoff and erosion can be reduced by mulches, since they can hold rainwater at the surface, thereby allowing it to penetrate the soil (Mupangwa et al., 2007).

As an organic cover crop mulch, buckwheat has been widely used because it is a short-season cover crop that is easy to kill, and is reported to extract soil phosphorus from the soil better than most grain cover crops (Clark, 2012). Maize residue mulch has also been reported to increase maize grain yield significantly, compared to no-mulch or control treatments (Clark, 2012). The evidence from various parts of the world shows that soil management options such as the use of maize residue and cover crop mulch can help increase maize yield, but there is limited information on how they can influence maize yield when applied on IRWH basins with bio-slurry as a fertilizer.

Rainwater harvesting is an innovative approach as a soil and water conservation and management tool that can help increase crop water use efficiency, thus increasing yields and reducing the likelihood of crop failure (Botha, 2006). It is defined as the process of concentrating rainfall as runoff from a large area (catchment area) to be used productively in a target area (Oweis et al., 2001). The use of RWH&C technologies, such as IRWH, growing cover crops and mulching to slow runoff can be used to increase water infiltration and increase the available water for crop production. According to Botha et al. (2003b), IRWH increased the yields of maize and sunflower by about 30% and 50%, respectively, in the long term, compared to conventional tillage. The IRWH technique tested for maize, sunflower and bean production on the Glen/Bonheim ecotope, resulted in significantly higher yields compared to conventional tillage (Botha et al., 2003b; Hensley et al., 2000). These studies showed that IRWH has been evaluated in other parts of the country and has been found to increase maize yields and rainwater productivity, but it is not known how maize will respond when IRWH is used with mulch in the basins and bio-slurry as a fertilizer.

Another viable strategy for small-scale farmers who have biogas digesters is the use of bio-slurry, which is produced from a mixture of cow dung, urine and water to produce biogas. This bio-slurry from cattle can be used as a potential source of soil nutrients for small-scale rural farmers.

The use of bio-slurry could provide a solution to chemical fertilizers, which are expensive. However, its nutrient content with respect to nitrogen, phosphorus and potassium is low compared to chemical fertilizers. This means that it may be necessary to apply large quantities of bio-slurry to meet the same level of these nutrients compared to chemical fertilizers. Another challenge with the use of bio-slurry is the variability in its nutrient content. This might be due to the fact that the properties of bio-slurry depend on many factors, such as the material used to produce it (Islam, 2006). Other factors that affect the effectiveness of bio-slurry include the forms of bio-slurry, the methods used to store the bio-slurry (Gurung, 1997), as well as its application rate and application methods (Bonten et al., 2014).

Various studies have been conducted on the effect of bio-slurry on crop production, and the results show that bio-slurry application positively influences crop performance. For example, Islam et al. (2010) evaluated the effects of bio-slurry on the production and quality of maize fodder and found that it increased maize biomass and nutrient content by 5 to 11% compared to the control treatments. In another study, Rahman et al. (2008) also found increases of 11% in maize biomass and nutrient content compared to the control with the use of cattle bio-slurry. While such studies demonstrate research efforts on bio-slurry in different parts of the world, many of the studies were limited to the evaluation of its effect on maize biomass and did not focus on grain yield. There is also limited information on the effect of the bio-slurry application rate on maize growth and development, grain yields and yield parameters. This study therefore seeks to evaluate the effect of bio-slurry application rates in combination with various other soil management options (bare soil, cover crop and mulch) on maize growth and yield under field conditions.

### 5.3.2 Material and methods

The croplands at both Krwakrwa and Upper Ncera were poorly fenced and not well maintained. Animals could therefore easily enter the croplands and destroy the crops and basins. A decision was then taken to conduct the cropland experiments in a more secure environment. The experiment was conducted at Fort Cox College, which is situated in Middledrift, approximately 45 km from King William's Town in the Eastern Cape. Fort Cox College is situated at 32.7450° S latitude and 27.0268° E longitude. The soil and climate at Fort Cox College is representative of that at Krwakrwa and Upper Ncera, so that results could be extrapolated to these villages.

Fort Cox receives an annual rainfall of 412 mm. The highest rainfall is received in autumn and summer, and the lowest rainfall is received in June and July. It has an average annual temperature of 18.3 °C.

#### *5.3.2.1 Experimental layout*

The experimental design was a randomised complete block design (RCBD), with treatment design, a split-split plot. The main plots were the different treatments, i.e. mulch, cover crop, manure and bare basin (with spread application, single application and water application, respectively). The sub-plots were different concentrations, i.e. 0, 3, 5 and 7 t ha$^{-1}$ (not all applicate to all the treatments – see below). It was compared over three years.

A tractor and basin plough were used to construct the IRWH structures. The IRWH basins were then covered with mulch, planted with a cover crop or left bare. These management strategies were then combined with the application of bio-slurry at various application rates. The total area for each plot was 81 m$^2$. The treatments were 1.5 m apart. This experiment had a total of 20 treatments x concentration interactions, replicated four times (Figure 5.4). The treatments were as follows:

- Mulch in basin with no slurry application (Mulch$_0$)
  - Mulch in basin with a single slurry application of 3 t ha$^{-1}$ at planting (Mulch$_3$)
  - Mulch in basin with a single slurry application of 5 t ha$^{-1}$ at planting (Mulch$_5$)
  - Mulch in basin with a single slurry application of 7 t ha$^{-1}$ at planting (Mulch$_7$)

- Cover crop in basin with no slurry application ($CC_0$)
  - Cover crop in basin with a single slurry application of 3 t $ha^{-1}$ at planting ($CC_3$)
  - Cover crop in basin with a single slurry application of 5 t $ha^{-1}$ at planting ($CC_5$)
  - Cover crop in basin with a single slurry application of 7 t $ha^{-1}$ at planting ($CC_7$)

- Manure in basin equivalent to 3 t $ha^{-1}$ slurry application before planting ($Manure_3$)
  - Manure in basin equivalent to 5 t $ha^{-1}$ slurry application before planting ($Manure_5$)

- Bare basin with no slurry application ($Spread_0$)
  - Bare basin with a spread application of 3 t $ha^{-1}$ slurry ($Spread_3$)
  - Bare basin with a spread application of 5 t $ha^{-1}$ slurry ($Spread_5$)
  - Bare basin with a spread application of 7 t $ha^{-1}$ slurry ($Spread_7$)

- Bare basin with a single surface application of 3 t $ha^{-1}$ slurry applied before planting ($Surface_3$)
  - Bare basin with a single surface application of 5 t $ha^{-1}$ slurry applied before planting ($Surface_5$)

- Bare basin with a single application of 3 t $ha^{-1}$ slurry incorporated into the soil at planting ($Incorporate_3$)
  - Bare basin with a single application of 5 t $ha^{-1}$ slurry incorporated into the soil at planting ($Incorporate_5$)

- Bare basin with water application equivalent to the water in 3 t $ha^{-1}$ slurry at planting ($Water_3$)
  - Bare basin with water application equivalent to the water in 5 t $ha^{-1}$ slurry at planting ($Water_5$)

The bare, mulch, cover crop and manure treatments can be used to compare various management options at different slurry application rates. The various bare treatments (surface application, incorporated and spread application) can be used to compare various application methods and timing of application.

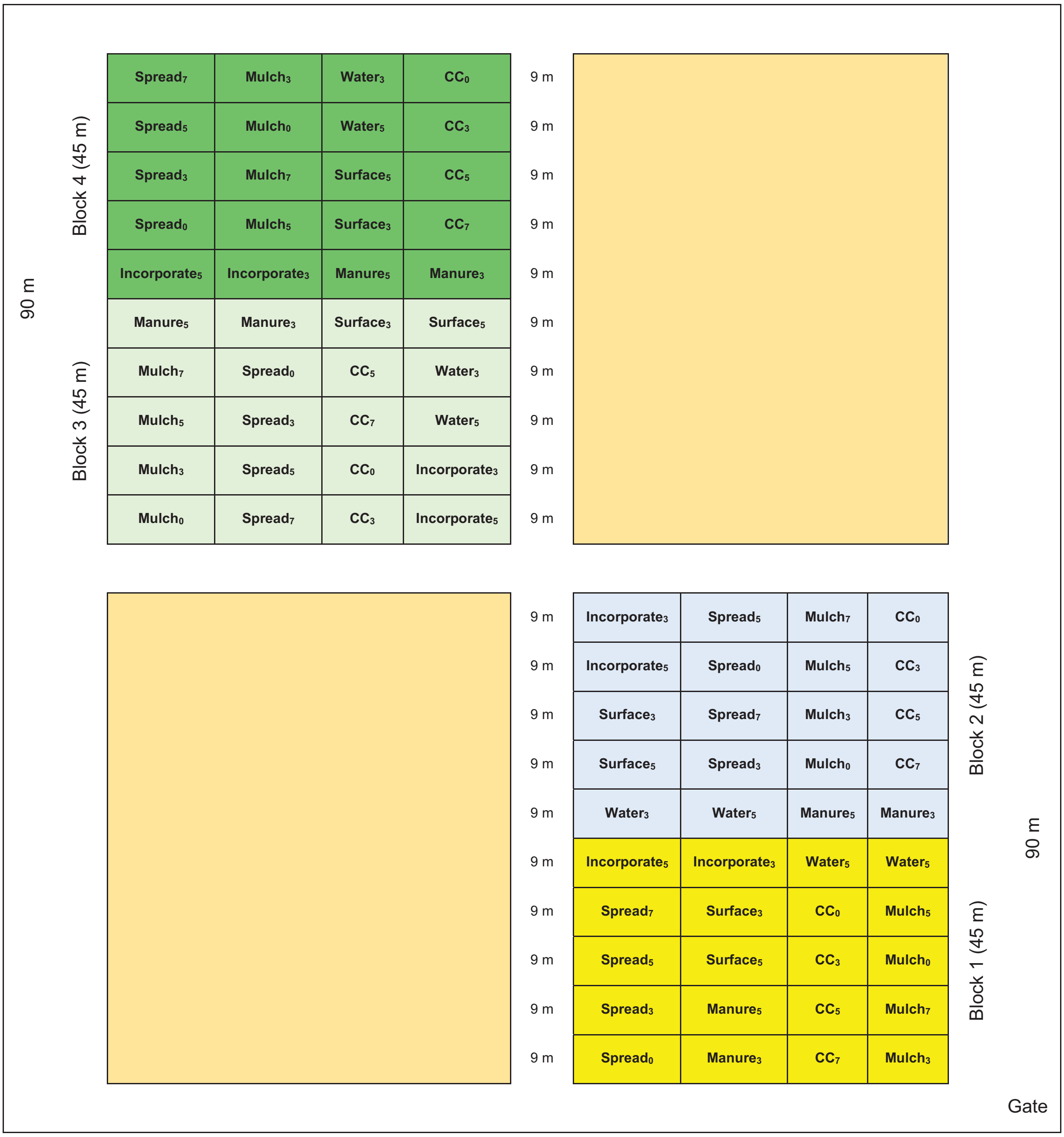



**Figure 5.4: Experimental layout for the Fort Cox/Valsrivier ecotope**

#### *5.3.2.2 Agronomic practices*

The IRWH basins were initially constructed around August to allow for the collection of runoff water during early spring. In the following years, basins were only maintained and not reconstructed.

For the mulch treatments, maize stover was applied just before planting in the basins for the first season. Thereafter, maize stalks were cut after the crop had been harvested, which were placed in the basins.

For the cover crop treatments, buckwheat was planted in the basins in spring. The buckwheat cover crop was very quick to establish and, as a result, only grew for about two months and died before the maize was planted. The buckwheat cover crop was quick to decompose, but it only decomposed after bio-slurry application. This means that the cover crops also disturbed the bio-slurry cake before its decomposition.

In all the plots with cattle manure in the basins, it was applied around September before the planting of maize in November, as it is done by the farmers. This was done to allow for the process of decomposition and the release of nutrients to the crop.

The application of different rates of bio-slurry was applied immediately after the maize had been planted. This was due to the fact that the nutrients in bio-slurry are said to be readily available. Where the application of bio-slurry was spread, it was applied as two split applications, one at planting and the second six weeks after planting. The chemical analysis of the bio-slurry used in the experimental plots is presented in Table 5.4. The bio-slurry and cattle manure samples were characterised for total nitrogen, total phosphorus, total potassium and micro-nutrients (Fe, Cu, Zn, Mn). The conductivity and pH of bio-slurry and cattle manure were analysed within two hours of sampling by digital conductivity and pH meter.

**Table 5.4: Chemical analysis of bio-slurry applied at the experimental plots at Fort Cox**

| **Moisture** (%) | **Total N** (%) | **P** (%) | **Ca** (%) | **Mg** (%) | **K** (%) | **Na** (mg $kg^{-1}$) | **Cu** (mg $kg^{-1}$) | **Fe** (mg $kg^{-1}$) | **Mn** (mg $kg^{-1}$) | **Zn** (mg $kg^{-1}$) | **pH** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 33.1 | 1.6 | 0.44 | 4.14 | 0.27 | 0.45 | 210 | 16 | 833 | 309 | 199 | |

The quantity of nitrogen applied in the bio-slurry plots was calculated from the availability of nitrogen in the bio-slurry. According to the results, the application rates were going to supply different amounts of nitrogen to the crop, 0 t $ha^{-1}$ (0 kg N), 3 t $ha^{-1}$ (48 kg N), 5 t $ha^{-1}$ (80 kg N), and 7 t $ha^{-1}$ (112 kg N). The equivalent nitrogen content of the various bio-slurry application rates is relatively low compared to commercial nitrogen application rates. However, it should be kept in mind that higher bio-slurry application rates would not be practical in a rural setting where the bio-slurry has to be transported from the bio-digesters at the homestead to the croplands.

In those plots where there was a split application of bio-slurry, the slurry was analysed before each application to avoid variation in nutrient composition. The same was done with cattle manure. The amount of water to be applied on the control plots was based on the amount of water found in the bio-slurry. This application of water in the control plots was done to make sure that the effect on bio-slurry plots would only be due to other bio-slurry benefits other than water.

The Roundup® Ready maize cultivar PAN 6R-680RR was used for this experiment as it helps in effective weed control during the maize-growing season. A row of maize was planted on both sides of the basin; one row on the side of the runoff area of the IRWH system and the other on the opposite side of the basin. Planting was done using a two-row maize planter. The planter was calibrated at 100 cm inter-row for all treatments for a plant population of 22,000 plants $ha^{-1}$. The seeds were planted 7 cm deep.

Weeds were controlled at pre-planting using the Roundup® (glyphosate) herbicide. The Roundup® (glyphosate) herbicide has an active ingredient of 480 g per litre and was applied at 5 ℓ $ha^{-1}$ before planting. A follow-up spraying was done to ensure maximum crop benefits and minimise crop-weed competition at 2.5 ℓ $ha^{-1}$ during the crop-growing stage. Problematic pests and diseases were controlled using chemical control methods. The agronomic information for the experiments conducted at Fort Cox College is presented in Table 5.5.

**Table 5.5: Agronomic information for the on-station experiments conducted at the Fort Cox/Valsrivier ecotope over four growing seasons**

| Season | Cultivar | Plant population (plants $ha^{-1}$) | Planting date | Physiological maturity |
|---|---|---|---|---|
| 20016/2017 | PAN 6R-680RR | 22,000 | 2017/02/07 | 2017/06/02 |
| 20017/2018 | PAN 6R-680RR | 22,000 | 2017/11/20 | 2018/03/15 |
| 20018/2019 | PAN 6R-680RR | 22,000 | 2018/11/28 | -*1 |
| 20019/2020 | PAN 6R-680RZDN8 | 22,000 | 2020/01/14 | 2020/05/08 |

*1 Nothing harvested, since cattle that entered the field destroyed the crop.

***Implementation of IRWH structures***

***Application of bio-slurry***

***Planting of maize***

***Installation of NWM access tubes***

***Chemical weed control***

***Cutting of maize for biomass determinations***

**Figure 5.5: Activities at the on-station experimental plots at Fort Cox**

#### *5.3.2.3 Data collection*

**Climate data**

Minimum and maximum temperatures, wind speed, wind direction and rainfall were recorded using the automatic weather station at the new Fort Cox College Campus. Rainfall was also measured manually at the experimental plots using a rain gauge to validate the data recorded at the automatic weather station. Climatic data was used to calculate some of the important parameters that influence the soil water content (SWC) on the Fort Cox/Valsrivier ecotope.

**Soil parameters**

*Profile description*

A profile pit was dug at the experimental plot. The profile was described in detail according to the Soil Classification Working Group (1991). The soil colour was read using a Munsell Colour Chart. Soil samples were taken from each diagnostic horizon and soil analyses were done at the ARC-SCW Laboratory in Pretoria using methods according to the Non-Affiliated Soil Analysis Work Committee (1990).

*Soil water content*

To monitor the SWC of the root zone in the on-station experiments, neutron water meter (NWM) access tubes were installed to a greater depth than the root zone. Measurements of SWC were carried out before planting and at planting, flowering and plant maturity at 300 mm depth intervals starting at 150 mm. This procedure ensured that the different pedological layers in the soil were adequately represented. A Campbell Pacific 503 DR NWM was used, which was calibrated for every soil layer by using gravimetric SWC measurements ($\theta$ m) and the bulk density of the soil. A range of NWM counts was made for each soil layer, under wet and dry conditions, and at the same time, samples for $\theta$ m determinations were taken close to the NWM access tubes. The $\theta$ m values for each soil layer were multiplied by the appropriate bulk density value to give the volumetric SWC ($\theta$ v) of that layer. In the event of rain, the SWC was measured before and after the event, depending on the logistics and whether it was realistic and feasible. The data was safely stored on the computer. Plant available water was calculated as SWC minus the lower limit of plant available water.

*Evaporation*

The procedure proposed by Tanner and Sinclair (1983) was used to separate evapotranspiration into its two components: evaporation from the crop (Ev) and evaporation from the soil surface (Es). The transpiration efficiency coefficient (k) was used to separate Es and Ev. The k value of 9.5 g $m^{-2}$ $mm^{-1}$ suggested by Tanner and Sinclair (1983) was used for the maize.

**Plant parameters**

*Biomass*

Biomass yield was determined from 36 plants per treatment at maize physiological maturity and expressed as oven dry mass in kg $ha^{-1}$. The plants were cut above ground and dried in the oven until a constant weight was measured at a temperature of 60°C. The biomass at physiological maturity was used to calculate the Harvest Index (HI).

*Grain yield*

Maize was harvested at physiological maturity to determine the grain yield by harvesting a statistically representative area of six rows of 10 m from the middle of each treatment. The cobs were harvested manually, then threshed using a threshing machine. The grain yield was recorded in kg $ha^{-1}$ at 13% grain moisture for all the treatments. The grain yield data was also used for calculating HI and RWP.

*Harvest Index*

The HI was calculated as the ratio of grain yield ($Y_g$) to the total above-ground biomass yield ($Y_b$) as shown in the following equation:

$$HI = Yg / Yb \quad (7)$$

where:

| | | |
|---|---|---|
| HI | = | Harvest Index |
| Yg | = | Grain yield (kg $ha^{-1}$) |
| Yb | = | Total above ground biomass (kg $ha^{-1}$) |

*Rainwater productivity*

Rainwater productivity is the ratio of grain yield produced over the total rainfall received during the production period. It is presented in the following equation:

$$RWP = Yg / Pp \quad (8)$$

where:

| | | |
|---|---|---|
| RWP | = | Rainwater productivity (kg $ha^{-1}$ $mm^{-1}$) |
| Yg | = | Grain yield (kg $ha^{-1}$) |
| Pp | = | Rainfall during the production period (mm) |

## Data analysis

All the data generated from this research was analysed using Microsoft Excel to determine the 95% confidence interval differences between the various treatments.

### 5.3.3 Results and discussion

In this section, the results for the evaluation of IRWH in combination with various soil management options and bio-slurry application rates are discussed.

#### *5.3.3.1 Soil*

The soil was classified as belonging to the Luckhoff family of the Valsrivier form (Soil Classification Working Group, 1991). The soil occurs in Land Type Fb881 and the experimental field at Fort Cox College lies on Terrain Unit 5 (Land Type Survey Staff, 2002). The experimental plots were located on a valley bottom with a straight 1% slope in a westerly direction.

A detailed soil profile description is presented in Appendix 2 The soil consists of a 300 mm thick very dark greyish brown clay loam orthic A-horizon with 14% clay, overlying a 500 mm thick dark greyish brown pedocutanic B-horizon with 19% clay on a 400 mm dark yellowish brown unconsolidated C-horizon with no visible signs of wetness with an 18% clay content (Table 5.6). The effective root zone is considered to be 1,200 mm.

The soil pH of the A-horizon is slightly alkaline with the B- and C-horizons being very alkaline. The potassium level was very low in the top soil and intermediate in the rest of the profile. The calcium level in all three horizons was also intermediate. A magnesium value of more than 300 mg $kg^{-1}$ in a soil is considered to be high; the average of all three horizons was more than six times higher (2,015 mg $kg^{-1}$). The soil's phosphorus levels were extremely high, exceeding the maximum level in all three horizons, especially in the A-horizon. According to the analysis, the salinity of the soil presents no problem to the growth of any crop. Physical analysis was done in seven fractions. For the full set of analysis results, see Appendix 3.

The most important soil characteristics of the Fort Cox/Valsrivier ecotope are described in Table 5.6. The drained upper limit of plant available water of the soil is 245 mm and the lower limit of plant available water is 122 mm, therefore the total extractable soil water is 123 mm for this Valsrivier soil form.

**Table 5.6: Important characteristics of the soil component of the Fort Cox/Valsrivier ecotope**

| Profile detail | | | | | | Soil water extraction properties | | |
|---|---|---|---|---|---|---|---|---|
| **Horizon** | **Diagnostic horizon** | **Depth (mm)** | **Colour** | **Clay (%)** | **BD (g $cm^{-3}$)** | **DUL (mm)** | **LL (mm)** | **TESW (mm)** |
| A | Orthic | 0–300 | Very dark greyish brown | 14 | 1.56 | 68 | 31 | 37 |
| B | Pedocutanic | 300–800 | Dark greyish brown | 19 | 1.60 | 101 | 50 | 51 |
| C | Unconsolidated without signs of wetness | 800–1200 | Dark yellowish brown | 18 | 1.60 | 76 | 41 | 35 |
| **Total** | | | | | | **245** | **122** | **123** |

BD = Bulk density; DUL = Drained upper limit of plant available water; LL = Lower limit of plant available water; TESW = Total extractable soil water

#### *5.3.3.2 Climate*

Rainfall, potential evaporation (ETo) and Aridity Index (AI) were divided into five sections as indicated in Table 5.7 in order to analyse each season separately and compare the data with the corresponding long-term means.

**Table 5.7: Precipitation, evaporative demand and Aridity Index values over four growing seasons (2016/17–2019/20) in relation to the long-term means for maize production on the Fort Cox/Valsrivier ecotope**

| Parameter | Season | Period | | | | |
|---|---|---|---|---|---|---|
| | | $F_p$ | $V_p$ | $R_p$ | $G_p$ | $P_p$ |
| P (mm) | 2016/17 | - | 100 | 49 | 149 | - |
| | 2017/18 | 267 | 75 | 126 | 200 | 467 |
| | 2018/19 | 252 | 58 | 66 | 124 | 376 |
| | 2019/20 | 197 | 171 | 98 | 269 | 465 |
| | **Mean** | **238** | **101** | **85** | **185** | **436** |
| | **Long-term mean** | **354** | **191** | **119** | **310** | **664** |
| ETo (mm) | 2016/17 | - | 234 | 111 | 345 | - |
| | 2017/18 | 453 | 297 | 177 | 474 | 927 |
| | 2018/19 | 712 | 321 | 196 | 516 | 1228 |
| | 2019/20 | 930 | 253 | 129 | 383 | 1313 |
| | **Mean** | **698** | **276** | **153** | **430** | **1156** |
| | **Long-term mean** | **750** | **340** | **205** | **545** | **1295** |
| AI (mm) | 2016/17 | - | 0.43 | 0.44 | 0.43 | - |
| | 2017/18 | 0.59 | 0.25 | 0.71 | 0.42 | 0.50 |
| | 2018/19 | 0.35 | 0.18 | 0.34 | 0.24 | 0.31 |
| | 2019/20 | 0.21 | 0.67 | 0.76 | 0.70 | 0.35 |
| | **Mean** | **0.38** | **0.38** | **0.56** | **0.45** | **0.39** |
| | **Long-term mean** | **0.47** | **0.56** | **0.58** | **0.57** | **0.51** |

$F_p$ = Fallow period; $V_p$ = Vegetative period; $R_p$ = Reproductive period; $G_p$ = Crop growing period; $P_p$ = Production period

Results from Table 5.7 indicate that the climatic conditions for crop production were very unfavourable over all four growing seasons. The average rainfall during the crop-growing period of 185 mm was 40% less than the corresponding long-term mean of 310 mm. The 2019/20 season was the most favourable season for crop production, but even during that year, the rainfall received was still far below the long-term mean. However, the evaporative demand (ETo) during the experimental period was lower than the long-term mean. If that was not the case, the crops would not have been able to survive under these conditions of water scarcity. The AI values were typical of a semi-arid area, characterised by hot, dry summers with a high evaporative demand.

The experimental plots were located adjacent to the plots where the students from Fort Cox College had conducted their own experiments. They often irrigated their plots, and sprinklers were left unattended. This resulted in some of the experimental plots receiving additional water that was not accounted for.

Although the rainfall was insufficient to sustain good crop growth, it was still possible to harvest a crop with a reasonable yield. This was because it was possible to increase the effective rainfall by making use of the IRWH technique. With this technique, runoff water was collected from the 2 m wide runoff strip, collected and stored in the basins. Unproductive water loss from the soil surface could be further minimised by the application of mulch in the basin area.

#### *5.3.3.3 Water balance components*

**Soil water content**

Plant available water at planting ($PAW_P$), plant available water at tasselling ($PAW_T$) and plant available water at physiological maturity ($PAW_{PM}$) for the root zone (1,200 mm) for the various treatments on the Fort Cox/Valsrivier ecotope over three maize growing seasons (2016/17−2019/20) are presented in Table 5.8. Only the results for the 3 and 5 t $ha^{-1}$ bio-slurry applications are presented so that the effect of the bio-slurry application rate on all soil management options can be compared.

The volume of water applied in the bio-slurry was too little to make any significant contribution to the soil water contents. It was expected that the treatments where mulch was applied would have a higher SWC because water loss due to evaporation from the soil surface was suppressed. However, this was not the case. Most of the rainfall received during the growing season occurred in the form of small rainfall events of less than 10 mm. The dry mulch behaved like a sponge and absorbed most of the rainfall, allowing very little water to infiltrate the soil profile. The mulch helped to create a cooler, more favourable cropping environment than the other soil management treatments. Decomposition of the mulch over time could have contributed to the release of nutrients that contributed to the higher yields.

According to Kumar et al. (2010), bio-slurry contains organic matter and fibre, which helps hold soil moisture and improves soil organic matter content, as well as water-holding capacity when applied to the soil. However, the water contained in the bio-slurry was insufficient to significantly increase the SWC at planting, flowering and harvest (Table 5.8).

Bio-slurry can also form a mulch when applied to the soil surface. This is because, after application, it covers the soil surface and forms a bio-slurry cake of organic material that can reduce evaporation from the soil surface (Kumar et al., 2010).

**Table 5.8: Plant available water at planting, tasselling and physiological maturity of the root zone (1,200 mm) for the various treatments on the Fort Cox/ Valsrivier ecotope over three growing seasons (2016/17−2019/20)**

| Parameter | Season | Soil management treatment and bio-slurry application (t ha$^{-1}$) | | | | | | | | | | | | | | | | | | | | Mean | LSD$_{(p=0.05)}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mulch | | | | Cover crop | | | | Manure | | Bare: surface application | | Bare: incorporate | | Bare: water equivalent | | Bare: spread application | | | | | |
| | | 0 | 3 | 5 | 7 | 0 | 3 | 5 | 7 | 3 | 5 | 3 | 5 | 3 | 5 | 3 | 5 | 0 | 3 | 5 | 7 | | |
| PAW$_P$ (mm) | 2016/17 | 107$^{abc}$ | 97$^{bc}$ | 112$^{abc}$ | 91$^{c}$ | 118$^{abc}$ | 112$^{abc}$ | 114$^{abc}$ | 108$^{abc}$ | 109$^{abc}$ | 114$^{abc}$ | 140$^{a}$ | 132$^{ab}$ | 117$^{abc}$ | 133$^{a}$ | 131$^{ab}$ | 110$^{abc}$ | 120$^{abc}$ | 110$^{abc}$ | 134$^{a}$ | 108$^{abc}$ | **116** | 36.0 |
| | 2017/18 | 134$^{bcdef}$ | 135$^{bcdef}$ | 123$^{f}$ | 129$^{ef}$ | 139$^{abcde}$ | 132$^{def}$ | 137$^{abcde}$ | 131$^{ef}$ | 130$^{ef}$ | 132$^{def}$ | 144$^{abcd}$ | 145$^{abc}$ | 142$^{abcde}$ | 147$^{ab}$ | 144$^{abcd}$ | 138$^{abcde}$ | 147$^{ab}$ | 145$^{abc}$ | 148$^{a}$ | 139$^{abcde}$ | **138** | 12.5 |
| | 2019/20 | 106$^{ab}$ | 109$^{ab}$ | 110$^{ab}$ | 107$^{ab}$ | 117$^{a}$ | 120$^{a}$ | 118$^{ab}$ | 97$^{b}$ | 109$^{ab}$ | 113$^{ab}$ | 120$^{a}$ | 116$^{a}$ | 121$^{a}$ | 121$^{a}$ | 118$^{a}$ | 114$^{a}$ | 119$^{a}$ | 120$^{a}$ | 120$^{a}$ | 118$^{a}$ | **115** | 16.5 |
| | **Mean** | **116** | **113** | **115** | **109** | **125** | **121** | **123** | **112** | **116** | **119** | **135** | **131** | **126** | **134** | **131** | **121** | **129** | **125** | **134** | **122** | **123** | |
| PAW$_T$ (mm) | 2016/17 | 74.4$^{cd}$ | 85$^{abcd}$ | 85$^{abcd}$ | 81$^{abcd}$ | 107$^{abcd}$ | 85$^{abcd}$ | 78$^{bcd}$ | 94$^{abcd}$ | 96$^{abcd}$ | 100$^{abcd}$ | 93$^{abcd}$ | 98$^{abcd}$ | 102$^{ab}$ | 88$^{abcd}$ | 88$^{abcd}$ | 91$^{abcd}$ | 104$^{ab}$ | 101$^{bcd}$ | 85$^{abcd}$ | 73$^{d}$ | **90** | 26.7 |
| | 2017/18 | 124$^{cde}$ | 122$^{de}$ | 124$^{cde}$ | 120$^{e}$ | 141$^{abcde}$ | 150$^{a}$ | 143$^{abc}$ | 135$^{abcde}$ | 140$^{abcde}$ | 129$^{abcde}$ | 143$^{abc}$ | 137$^{abcde}$ | 129$^{abcde}$ | 146$^{ab}$ | 141$^{abcde}$ | 138$^{abcde}$ | 130$^{abcde}$ | 134$^{abcde}$ | 128$^{abcde}$ | 143$^{abc}$ | **135** | 21.0 |
| | 2019/20 | 101$^{a}$ | 98$^{a}$ | 97$^{a}$ | 101$^{a}$ | 114$^{a}$ | 107$^{a}$ | 107$^{a}$ | 96$^{a}$ | 101$^{a}$ | 98$^{a}$ | 111$^{a}$ | 91$^{a}$ | 104$^{a}$ | 104$^{a}$ | 111$^{a}$ | 103$^{a}$ | 94$^{a}$ | 96$^{a}$ | 96$^{a}$ | 93$^{a}$ | **100** | 27.6 |
| | **Mean** | **100** | **102** | **102** | **101** | **120** | **114** | **109** | **99** | **112** | **109** | **116** | **109** | **112** | **113** | **113** | **111** | **109** | **110** | **103** | **103** | **108** | |
| PAW$_{PM}$ (mm) | 2016/17 | 62$^{abcdef}$ | 40$^{f}$ | 49$^{def}$ | 45$^{ef}$ | 68$^{abcdef}$ | 71$^{abcdef}$ | 70$^{abcdef}$ | 88$^{ab}$ | 80$^{bcde}$ | 67$^{abcdef}$ | 76$^{abcde}$ | 90$^{a}$ | 56$^{bcdef}$ | 55$^{cdef}$ | 87$^{ab}$ | 49$^{def}$ | 93$^{a}$ | 74$^{abcde}$ | 83$^{abc}$ | 90$^{a}$ | **70** | 31.4 |
| | 2017/18 | 121$^{g}$ | 127$^{fg}$ | 130$^{cdef}$ | 130$^{cdef}$ | 147$^{abc}$ | 148$^{ab}$ | 141$^{abcdef}$ | 131$^{bcdefg}$ | 142$^{bcdef}$ | 143$^{bcdef}$ | 145$^{bcde}$ | 141$^{abcdef}$ | 126$^{fg}$ | 148$^{ab}$ | 151$^{a}$ | 147$^{abc}$ | 140$^{abcdef}$ | 134$^{abcdefg}$ | 128$^{fg}$ | 139$^{abcdef}$ | **138** | 17.4 |
| | 2019/20 | 103$^{a}$ | 105$^{a}$ | 104$^{a}$ | 106$^{a}$ | 112$^{a}$ | 112$^{a}$ | 115$^{a}$ | 108$^{a}$ | 108$^{a}$ | 109$^{a}$ | 118$^{a}$ | 112$^{a}$ | 110$^{a}$ | 110$^{a}$ | 115$^{a}$ | 114$^{a}$ | 105$^{a}$ | 109$^{a}$ | 108$^{a}$ | 105$^{a}$ | **109** | 27.3 |
| | **Mean** | **96** | **91** | **95** | **94** | **109** | **110** | **109** | **109** | **111** | **106** | **113** | **114** | **97** | **104** | **118** | **103** | **113** | **106** | **106** | **111** | **106** | |
| RSE (%) | 2016/17 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | **-** | |
| | 2017/18 | 28 | 33 | 27 | 30 | 26 | 23 | 25 | 14 | 17 | 25 | 25 | 21 | 34 | 39 | 23 | 30 | 24 | 32 | 27 | 23 | **26** | |
| | 2019/20 | -9 | -9 | -11 | -14 | -19 | -16 | -14 | -19 | -19 | -17 | -16 | -14 | -7 | -16 | -19 | -19 | -14 | -7 | -6 | -12 | **-14** | |
| | **Mean** | **9** | **12** | **8** | **8** | **3** | **3** | **5** | **-3** | **-1** | **4** | **5** | **4** | **13** | **12** | **2** | **6** | **5** | **12** | **11** | **5** | **6** | |

Different superscripts within a row indicate a significant difference ($P \le 0.05$); Values with similar superscripts are not significantly different ($P \le 0.05$).

**Evapotranspiration**

Results of the separation of evapotranspiration into evaporation from the soil surface and transpiration (evaporation from the crop) are presented in Appendix 4. These provide the opportunity to analyse the general effect of the various soil management options and slurry application rates on ET, Ev and Es.

Over the three maize-growing seasons where a crop was harvested, the evapotranspiration of individual treatments varied between 167 mm and 283 mm with an average of 223 mm. The differences between the various treatments were small and not significant. As expected, the mulch treatments had the highest Ev values. From visual observations, it was clear that the mulch treatments had the biggest plants. With a bigger photosynthesis factory, more water could move through the plant and was lost to the atmosphere through the stomata. Contrary to what was expected, the mulch treatment did not induce the lowest Es. Since the maize stalks formed a thick mulch blanket in the basins of the IRWH structures, it was assumed that mulching was the most effective management strategy to minimise Es losses. However, Es from the cover crop treatments was, on average, 3% less than that of the mulch treatments. As explained earlier, the buckwheat cover crop was planted in the basins more than two months earlier than the maize crop. By the time the maize seedlings were established, the cover crop had already completed its life cycle. The decomposing buckwheat residues formed a thin mulch blanket in the basin that was more effective in minimising evaporation from the soil surface than the mulch treatment itself. The buckwheat residue’s blanket was thinner than that of the mulch treatment, but much denser. Vapour from the soil surface could therefore “escape” much more easily through the maize stalks with large open spaces in between.

### *5.3.3.4 Yield response*

Grain and biomass yields and the Harvest Index for all the treatments are summarised in Appendix 5. Grain yields for treatments with 3 and 5 t ha$^{-1}$ slurry applications are presented graphically in Figure 5.6.

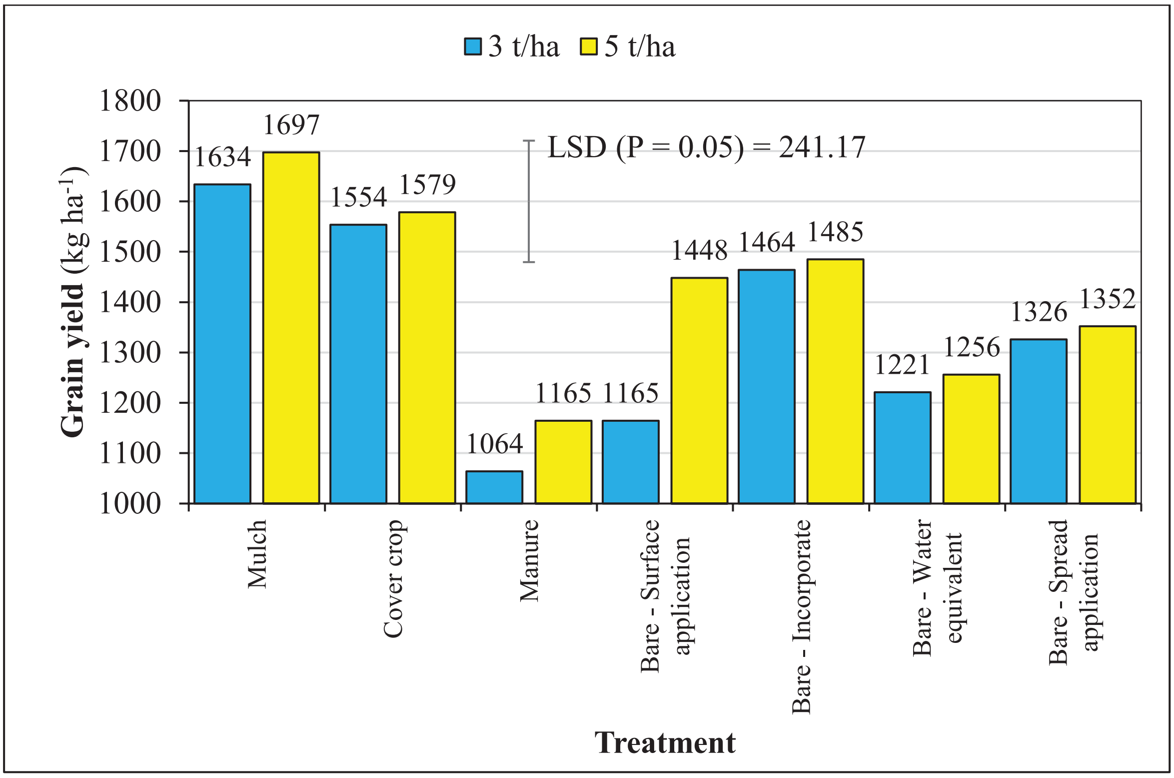



**Figure 5.6: Average grain yield (kg ha-1) for the various treatments on the Fort Cox/Valsrivier ecotope over three maize-growing seasons (2016/17–2019/20)**

Over the experimental period, the grain yields of individual treatments varied between 740 and 2,251 kg ha$^{-1}$ with a yield trend of mulch > cover crop > bare: incorporate > bare: surface application > bare: spread application > bare: water equivalent > manure (Appendix 5). This was expected, as mulching usually minimises evaporation from soil surface losses and creates a cooler cropping environment with a higher SWC. The higher SWC normally results in higher daily evapotranspiration, bigger plants and especially higher daily evapotranspiration during the grain filling stage, hence increasing the rate of photosynthetic supply to the grains, which is critical for optimum seed filling. Unfortunately, the soil moisture readings did not confirm the higher PAW for the mulch treatments. In contrast to what was expected, the treatment where manure was applied to the soil surface resulted in the lowest yields. The cattle dung cake dried out and lay undisturbed on the soil surface. Insufficient rainfall occurred to moisten the cattle manure sufficiently to stimulate microbial activity. The cattle manure was therefore not digested and nutrients did not leach into the soil. The cattle manure did not therefore provide the anticipated benefits.

Soil management options (mulch and cover crops) had a bigger impact on grain yield than the application of bio-slurry. The bio-slurry application rates used in this experiment were too low to make any significant contribution to grain yield. The application rate of bio-slurry should be much higher to be of real value. However, its practicality in a rural setting is questionable. Where villagers have bio-digesters and are able to produce bio-slurry for use as an organic fertilizer, it is produced in small quantities. This is not a viable option and is insufficient for use on a larger scale on the croplands. The bio-slurry produced at homestead bio-digesters can be used with much greater success in the homestead gardens. The time, effort and transport cost to take the bio-slurry from the homestead to the cropland is not an economically viable option. The return-on-investment gained from the yield increases will be low.

In the 2017/18 growing season, soil management options had no significant effect on grain yield. This could also be attributed to rainfall distribution during the growing season, with rainfall mostly received at the beginning of the season (October and November). Even though this gave maize an advantage in terms of initial growth and development, most of that rainfall was received in October before the maize was planted. Maize was planted towards the end of November after most of the rain had been received. This rainfall distribution did not give soil management options a chance to show their water conservation abilities because, by the time the maize had been planted and soil management option treatments applied, most of the rain had fallen already. Aslam et al. (2013) reported that a shortage of water to the maize crops results in reduced grain yield if water deficit occurs during the critical growth stages (from tasselling to grain filling).

Experimental results have revealed that the bio-slurry application rate, application method and timing of application are important considerations.

**Application rate**

Bio-slurry was applied at a rate of 0, 3, 5 and 7 t ha$^{-1}$. With all the treatments, the highest yields were obtained with the highest application rate (Appendix 5). This is a clear indication that grain yields can be increased even further by applying bio-slurry at much higher application rates. Biomass and grain yields did not increase exponentially with the higher bio-slurry application rates. This could be due to the loss of nutrients, especially nitrogen from bio-slurry later in the growing season due to it being exposed to sunlight.

According to Gungula et al. (2003), an increase in nutrients, especially nitrogen, enhances the vegetative growth of maize and increases the resource capacity of the plant by increasing the number of leaves produced per plant. According to Mollah and Iswoyo (2018), bio-slurry can be a good fertilizer because it contains various minerals needed by plants, such as nitrogen, phosphorus, magnesium, calcium, potassium, copper and zinc. Parwata et al. (2016) reported that the application of bio-slurry can increase the growth of plants in the form of an increased number of leaves, plant height and stem diameter. This is because the plants can utilise nutrients, which are obtained from bio-slurry for their optimal growth, and that can result in increased yield.

However, it should be kept in mind that over-application of organic fertilizers, such as bio-slurry, can reduce plant growth (Warnars and Oppenoorth, 2014; Boateng et al., 2006). Results from the current study did not fully support the findings of any of these studies. This could be due to the fact that the application rates were too low to make any significant contribution to plant nutrition.

**Application method**

Bio-slurry can either be applied on the soil surface or incorporated into the soil. Where it was applied on the soil surface, it had dried out and formed a thin crust on the soil surface. This crust then had to be broken so that the nutrients could be leached into the soil during a heavy rainfall event. This can be time consuming and is not a practically viable option. Where bio-slurry was incorporated into the soil, at or before planting, the crop was able to benefit directly from the bio-slurry application, since the nutrients in the bio-slurry are readily available and can be taken up directly by the crop roots. Research results have revealed that slightly higher yields are obtained when bio-slurry is incorporated into the soil (Appendix 5 and Figure 5.6).

The bio-slurry was applied on the surface of the entire basins in all treatments, except the control treatment where there was no bio-slurry application. This might have led to nitrogen loss due to volatilisation, which normally results in the fertilizer value of bio-slurry being reduced later in the season. According to Karki and Expert (2006), incorporating bio-slurry into the soil immediately after application is considered to be the best application method, because the quality of bio-slurry deteriorates when exposed to the sun and important plant nutrients can also be washed away by rain if the bio-slurry is not incorporated into the soil. Therefore, incorporating any form of bio-slurry into the soil has been found to be beneficial as it reduces nitrogen loss through volatilisation (Al-Turki et al., 2004).

In this experiment, the bio-slurry application rates did not have a significant impact on biomass and grain yield because it was applied on the surface of the basins. Surface application might have encouraged the loss of nutrients. Nutrients, such as nitrogen, might be lost through volatilisation due to exposure to sunlight, and some could have been leached by rainwater. Therefore, the best results were obtained by applying sound soil management practices (mulching and cover crops).

**Time of application**

Bio-slurry can be applied before, with or after planting, either as a single or as a spread application. Where the bio-slurry was applied in a single application before or with planting, better crop performance was achieved. It can be argued that the crop benefitted more from the larger volume of water from a once-off application, instead of the small insignificant quantities it received with the spread application. The total amount of nutrients the crop received from the single or spread application stays the same, but with the larger single application, more water can infiltrate into the soil and increase the SWC, contributing to higher yields. With the smaller spread applications, most of the water evaporated even before it infiltrated into the soil. Where 5 t ha$^{-1}$ of bio-slurry was applied as a single application to the bare basins, it gave an average yield of 1,448 kg ha$^{-1}$. However, where it was applied as a split application (half at planting and half six weeks after planting), it gave an average yield of 1,352 kg ha$^{-1}$ (Figure 5.6). The single application provided, on average, only a 7% higher yield than the split application, which might seem insignificant. However, for a rural small-scale farmer who depends on his own production for household food security, it might be the difference between enjoying a plate of food and going to bed hungry.

#### *5.3.3.5 Biomass response*

The biomass yields at physiological maturity of individual treatments over the experimental period varied between 3,305 and 6,939 kg ha$^{-1}$, with a similar pattern to that of the grain yields: mulch > cover crop > bare: incorporate > bare: surface application > bare: spread application > bare: water equivalent > manure. The Harvest Index of individual treatments varied between 0.22 and 0.39 (Appendix 5).

#### *5.3.3.6 Rainwater productivity*

Precipitation use efficiency (PUE) and RWP for the various treatments on the Fort Cox/Valsrivier ecotope over the three maize growing seasons (2016/17−2019/20) are presented in Appendix 6.

The PUE is based on rainfall received during the growing period and gives an indication of the ability of the crop to convert water into food. The RWP takes into account the rainfall during the production period, which includes the growing period and the fallow period. The PUE of individual treatments varied between 4.6 and 9.7 kg grain $ha^{-1}$ $mm^{-1}$ rain during the experimental period. The RWP values varied between 2.6 and 4.8 kg grain $ha^{-1}$ $mm^{-1}$ rain during the experimental period. Both parameters followed the same trend as the yields.

#### *5.3.3.7 Relative performance*

In order to compare treatments, all yield and other relevant parameters (HI, PAW, Es, Ev, Es/ET, PUE, RWP) were expressed in relative units. For each treatment, the average yield obtained over the three growing seasons was used to calculate the relative yield. For each parameter, the treatments with the highest value had a relative value of 1. Corresponding values of other treatments were then expressed in terms of the treatment with a relative value of 1. For example, if 1,700 kg $ha^{-1}$ was harvested from the mulch treatment and 1,100 kg $ha^{-1}$ was harvested from the manure treatment, then the relative yield of mulch was taken as 1 and manure would be 0.65, since 1,100 divided by 1,700 equals 0.65. An example of the treatments that received 5 t $ha^{-1}$ bio-slurry application or equivalent is presented in Figure 5.7. Similar trends were observed with bio-slurry application rates of 0, 3 and 7 t $ha^{-1}$. The overall best performance was received where an organic maize stover mulch was applied in the basins. The poorest performing treatment was where manure was applied in the basins. The beneficial effect of sound soil management practices (mulch and cover crop) in combination with bio-slurry as organic fertilizer was clearly demonstrated with this experiment. Mulching induced the best performance due to its ability to conserve soil moisture, regulate soil temperature, improve soil health and fertility, and suppress weed growth.

The low performance of the manure treatments was surprising. Normally, manure increases crop yields, since the organic material is decomposed and slowly converted to inorganic nitrogen to be taken up by the plant. In addition, the increased levels of other nutrients and improvements in the soil's physical properties also contribute to yield increases. This positive response to manure application is observed where the dry cattle dung cake is broken up into smaller pieces and incorporated into the soil. However, with this experiment, cattle manure was applied as a surface application. Insufficient rainfall occurred to moisten the dry cattle dung cake sufficiently to stimulate microbial activity. Substituting manure for commercial fertilizer has positive societal benefits for food security (increased yields) and for environmental protection (less nitrogen loss and lower greenhouse gas emissions) if properly incorporated into the soil.

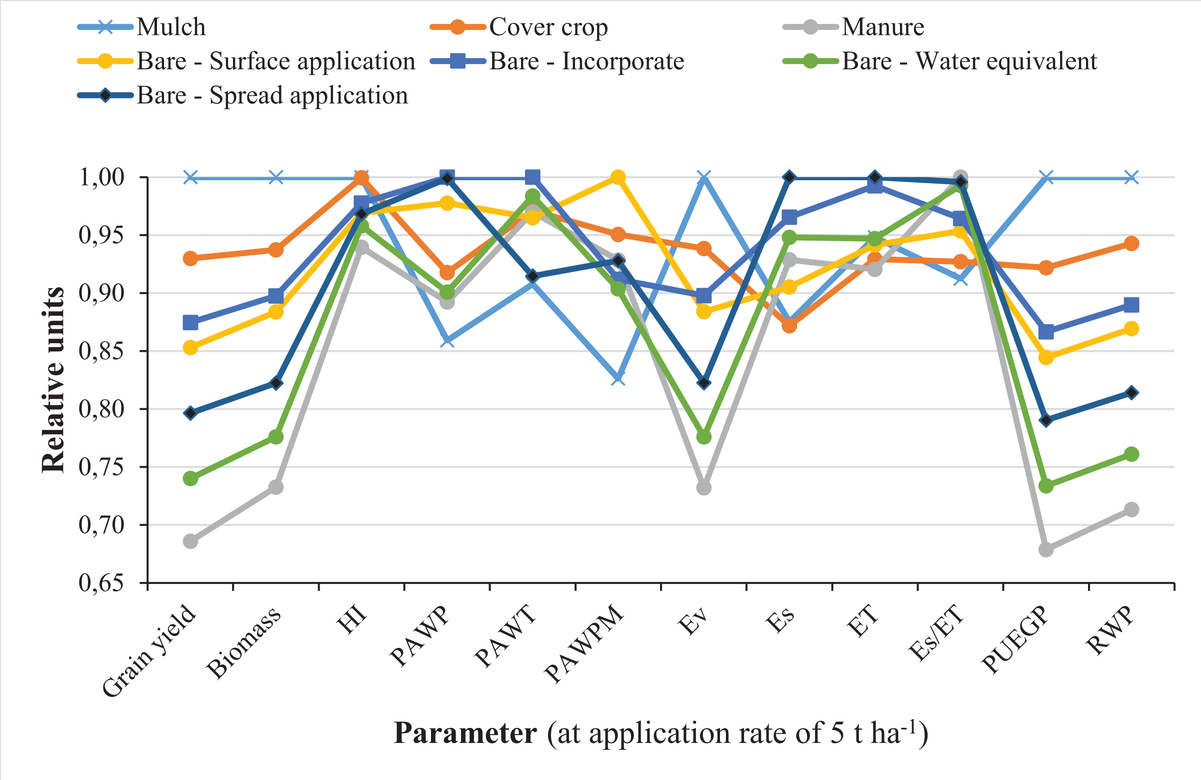



**Figure 5.7: Average relative values for crop- and water-related parameters for the various treatments on the Fort Cox/Valsrivier ecotope over three maize-growing seasons (2016/17–2019/20)**

### 5.3.4 Summary

The study was conducted at Fort Cox College over four seasons (2016/17–2019/20) as a four (0, 3, 5 and 7 t ha$^{-1}$ bio-slurry application rates) by three (maize-stover mulch, cover crop and bare soil basins) factorial experiment replicated four times in an RCBD, under IRWH. Data for maize biomass and grain yield was collected at harvesting. Maize biomass and grain yield data was used to calculate the Harvest Index. Bio-slurry application increased the maize biomass, grain yield and Harvest Index, but the increase was not significant. Even the highest bio-slurry application (7 t ha$^{-1}$) was too low to result in significant increases. Where bio-slurry was applied on the soil surface, it formed a bio-slurry cake on top of the soil surface in the basins that suppressed evaporation from the soil surface, while supplying plants with nutrients. It was therefore concluded that maize-producing small-scale farmers could make use of bio-slurry as an organic fertilizer if it can be applied at much higher application rates, while mulching and cover crops are suitable soil management options when producing maize using IRWH.

# CHAPTER 6: CONSERVATION OF RANGELANDS FOR IMPROVED RAINFALL USE EFFICIENCY, WATER USE EFFICIENCY AND WATER USE PRODUCTIVITY

## 6.1 INTRODUCTION

Agriculture is the largest user of freshwater resources worldwide. There are increasing concerns about the consequent impact of biofuel production on water consumption and quality. The ever-increasing human population is resulting in an increased demand for fresh water. Therefore, there is an increased emphasis on WUE in biomass production. In the arid and semi-arid regions, the annual productivity of agricultural systems is largely driven by precipitation. Many regions of the world are dependent on dryland farming for food production, which makes agronomic practices to increase WUE crucial. In most parts of the world, water remains the most limiting factor for agricultural production following improvements in soil fertility achieved with the increase of fertilizer application and the return of crop stubble since the 1980s (Hu et al., 2015). According to Hendrickson et al. (2013), water inputs for dryland farming systems are either water stored in the soil profile or water received as precipitation. The increasing water resource scarcity in arid rangelands is further constrained by an increase in human and livestock population, which requires plants with higher WUE. In most areas where climate change is exacerbating the negative effects of water scarcity, there is a need for research to maximize the WUE of various cultivated crops and grasses, especially in the dry rangelands. Livestock production in most arid rangelands of the world faces the challenge of inadequate forage supply as a result of prevailing water deficit that reduces feed supply. According to Koech et al. (2015), there are three options for the efficient utilization of available water to increase productivity in arid areas. These include the following:

- Increasing water productivity by reducing losses
- Improving the utilization of rainfall and intensifying rain-fed agriculture
- Pursuing alternative water sources for pasture and crop production

The aforementioned options may contribute to WUE enhancement by reducing water losses and increasing the productivity of pastures and crops in the arid rangelands. Water use efficiency can be measured on a seasonal or an annual scale and is important for understanding the management of dryland plant production systems. Enhancements in agricultural WUE depend on productivity gains at the field level and are quantified by consistent increases in outputs per unit of input. For dryland farmers, this can be equated to greater pasture and animal production per unit of water input. Inadequate rainfall frequently limits pasture production, particularly during winter. Rangelands are water-limited ecosystems where biomass production is greatly influenced by temperature, humidity, radiation, precipitation sequences, climatic variability and numerous other factors besides the WUE of the individual plants themselves (Emmerich, 2007). Like economics, pasture production is about supply (of water from the soil) and demand (for water by the pasture). Dry matter produced per mm of water used is a determinant of how efficiently plants utilise water (Beef and Lamb, 2014).

Therefore, it is important to gain an understanding of how pasture plants and grasses, under rainfed conditions, utilise available water as efficiently as possible (Moot et al., 2008). Moisture stress of dryland pastures is common over winter and early spring in summer rainfall areas. During these periods, the monthly potential evapotranspiration generally exceeds rainfall. This results in a long-term average potential soil moisture shortage amounting to about 430 mm $yr^{-1}$.

Water stress is relieved by spring or summer rain, which re-establishes the sward before cold winter temperatures restrict pasture growth (Tonmukayakul et al., 2008). Most of the pasture production in these areas occurs in summer when soil moisture is at or near field capacity and soil temperatures are on a rise, annually. The efficiency with which pastures utilise this available soil water throughout the growing season is therefore an essential contributor to annual pasture production (Mills et al., 2008).

The plant's adaptive abilities to the predominant unpredictable and highly variable climatic conditions determines the plants' survival in arid and semi-arid regions. Water use, WUE and the extraction of soil water differ among plant species and cultivars over growing seasons (Rao and Northup, 2009). Climatic uncertainties have caused range grasses to develop resistance or tolerance levels to the regular dry seasons and droughts. Gaining an understanding of water stress tolerance by grasses is vital in pasture management when it comes to water supply and choosing adapted species that depend on climatic conditions. Various grass species have an inherent genetic make-up, enhancing their diverse adaptation to water stress during droughts. Some of the adaptation mechanisms include, but are not limited to, rooting depth, pattern and distribution, seed germination rates, leaf characteristics and stem leaf ratios, among others (Kipchirchir et al., 2015).

Water use efficiency is a crucial component of a plant's adaptation to drought (Lucero et al., 2000). During drought periods, pastures are exposed to water stress and respond in different ways. These include, but are not limited to, reduction of transpiration rates, leaf rolling and growing leaf hairs. However, this may lead to reduced pasture yields, but enhancement of survival, which is more crucial in arid environments. This process differs among grass species that are subject to plant root and leaf characteristics. For instance, *Cynodon dactylon* (Bermuda grass) and *Medicago sativa* (alfalfa) have deep roots that enhance the utilisation of water in the lower soil profile (Schenk and Jackson, 2002a; 2002b). The water stress tolerance of grasses and pastures is one of the considerations in selecting drought-tolerant species that are suitable for drylands in the face of climate variability and change. Pasture productivity is crucial to livestock producers in arid and semi-arid environments. Therefore, there is a need to promote proper pasture management and choice of species that are adapted to frequent water deficits. This will ensure a reliable supply of forage of a good quantity and quality in the face of climate change (Schenk and Jackson, 2002a; 2002b). Soil water is the most limiting environmental factor. It determines plant production, thus the selection of species for dryland pasture production should be based on the efficiency of using available water (Snyman, 1994). To realize increased WUE, the system needs to be taken into account holistically. The system includes the soil, the climate and the plant. Various abiotic factors affect the WUE of plants. Some of these abiotic factors are environmental factors such as soil nutrient status (nitrogen and phosphorus), soil moisture, soil type and soil management practices. With increasing concern about the availability of water resources in both irrigated and rain-fed agriculture, there is a renewed interest in trying to develop an understanding of how WUE can be improved and how farming systems can be modified to be more water-use efficient. In rain-fed agriculture, WUE is linked to the effective use of precipitation because there is no other source of water.

Rain-fed agriculture remains the dominant crop and forage production system throughout the world. The stability of food and fibre production requires an increase in precipitation use efficiency (Hatfield et al., 2001).

The Eastern Cape has high livestock numbers in communal areas, where farmers cannot afford to buy supplementary feed for their animals during the drier seasons. The former homeland areas, within which the Krwakrwa communal area falls, consist of old arable lands, which used to be planted to maize, but are now lying fallow and are currently used as a grazing resource for livestock. These old arable lands are dominated by less palatable grasses, known as increaser species, such as *Sporobolus africanus*, *Cynodon dactylon* and *Eragrostis plana*. These lands have been abandoned for various reasons, which include soil nutrient depletion that has occurred throughout the decades when they were still under maize production.

In an attempt to address forage deficit to fodder flow throughout the seasons and to rehabilitate the nutrient-poor soils, four forage leguminous pasture species (*Lotus corniculatus*, *Lespedeza cuneata*, *Trifolium repens* and *Trifolium vesiculosum*) were planted in the old, abandoned lands in the Krwakrwa communal area. These species were evaluated in terms of their dry matter yield production and their potential to improve soil and plant nutrient status.

The general aim of the trial was to bridge the forage deficit gap by evaluating appropriate RWH&C techniques, RUE and WUE for increased pasture and livestock production. The specific objectives were as follows:

- Determine the effect of mechanised basins on the quantity of the biomass production of various grass-legume mixtures planted in the old lands
- Determine the effect of planting various pasture species on the overall quantity of dry matter produced in the Krwakrwa old lands during different seasons
- Determine species composition and landscape condition in the old arable lands

## 6.2 SITE DESCRIPTION

The study site is located at Krwakrwa Village in Alice, in the central parts of the Eastern Cape. It is in the undulating foot slopes of the Amathole Mountain in the south of the Hogsback (centred around 32°44'42 S; 26°54'17 E). The study had three sites at Krwakrwa Village, within two different vegetation types: Bhisho thornveld and Amathole montane grassland (Mucina and Rutherford, 2006). The area has moderately undulating topography, which ranges from steep mountainous escarpments to a moderately rolling mixture of grassland and savanna, sometimes in shallow, incised drainage valleys. Amathole vegetation is characterised by short grassland with high species richness of forbs, and soils are derived on sedimentary rocks of the Beaufort Group (Karoo Supergroup) overlaid by deep, freely drained, highly weathered soils. Weakly developed lithosols are also found in places.

In the Bhisho thornveld, vegetation mainly comprises open savanna, characterised by small Acacia trees with a short to medium, dense, sour grassy undercanopy of trees (Mucina and Rutherford, 2006), usually dominated by *Themeda triandra* when in good condition. A diversity of other woody species also occurs, often increasing under conditions of overgrazing. Soils in these areas are of mudstone parent material with subordinate sandstone of the Adelaide Subgroup (Beaufort Group, Karoo Supergroup) and are intruded by Karoo dolerite dykes and sills. The substrate is primarily loamy soils, but there is significant variability.

Precipitation of summer rainfall with some rain in winter is common in areas covered by Bhisho thornveld, and in the Amathole montane grasslands, rainfall changes the pattern with spring precipitation that peaks in late summer. The mean annual rainfall in this area varies from 500 mm in areas dominated by Bhisho thornveld vegetation to 670 mm in the Amathole montane grasslands (Mucina and Rutherford, 2006).

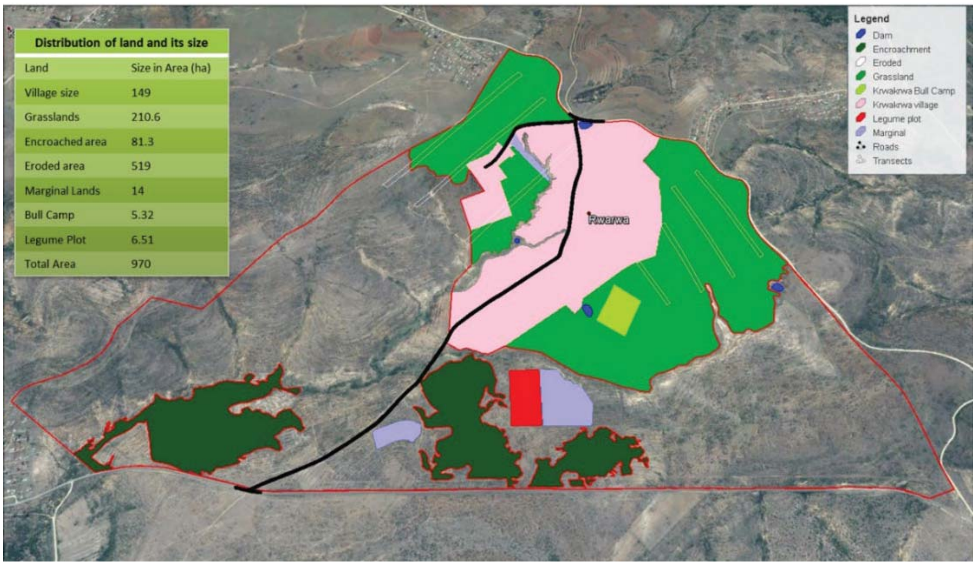



**Figure 6.1: Map of the study site indicating the rangelands at Krwakrwa Village**

## 6.3 MATERIAL AND METHODS

### OLD LANDS

An old land of about 6.51 ha was used as the experimental site where three forage legumes [*Lotus corniculatus* (bird's foot trefoil)*, Lespedeza cuneata* (Sericea lespedeza) and *Trifolium repens* (white clover)] were intercropped with one grass species (*Eragrostis curvula*). The planting of grasses and legumes was done during September 2017. A no-till planter was used to plant seeds of both grass and legumes into the old land (at the same time as a mixture). A ripper was used to implement the mechanised basins. Based on the soil analysis results, the phosphorus level was corrected to the level of 20 mg P kg$^{-1}$ by applying 50 kg of superphosphate per hectare, once off at planting. The plots, measuring 20 m x 15 m, were arranged in an RCBD and each treatment was replicated four times. Prior to planting, legume seeds were mixed with the appropriate inoculant by hand and mechanized basins were implemented accordingly. Seasonal herbage production was measured in a 0.25 m$^2$ quadrat to harvest biomass in all the experimental plots. All the herbaceous samples were cut using hand shears at approximately 5 cm above soil level. The following parameters were measured and analyzed: species composition, landscape function and dry matter production. Grass species composition data, in the form of the step point and landscape functional analysis method, were used to determine the landscape and species composition. All biomass data production was done seasonally (i.e. in spring, summer and autumn) throughout the duration of the experiment. Statistical data analysis was done using a two-way analysis of variance of the generalized linear model procedure of the SAS 2001 statistical program. Results obtained from the study are expected to generate information regarding the effect of implementing RWH techniques and grass-legume intercropping on the total dry matter production of pastures in old arable lands in the Krwakrwa communal area.

### RANGELANDS

### 6.3.1 Experiment layout and design

Enclosure cages of 4 m$^2$ were systematically placed in line transects on the rangelands with an interval of 200 m in between cages. Transects were laid along the slope gradient with top, middle and bottom lines and parameters measured inside and outside adjacent to each cage. These cage transects were replicated in three camps or sites (in two veld types). Aluminium metal access cubes of different lengths were inserted in at least three cages with reference points per row in all three study sites to measure SWC.

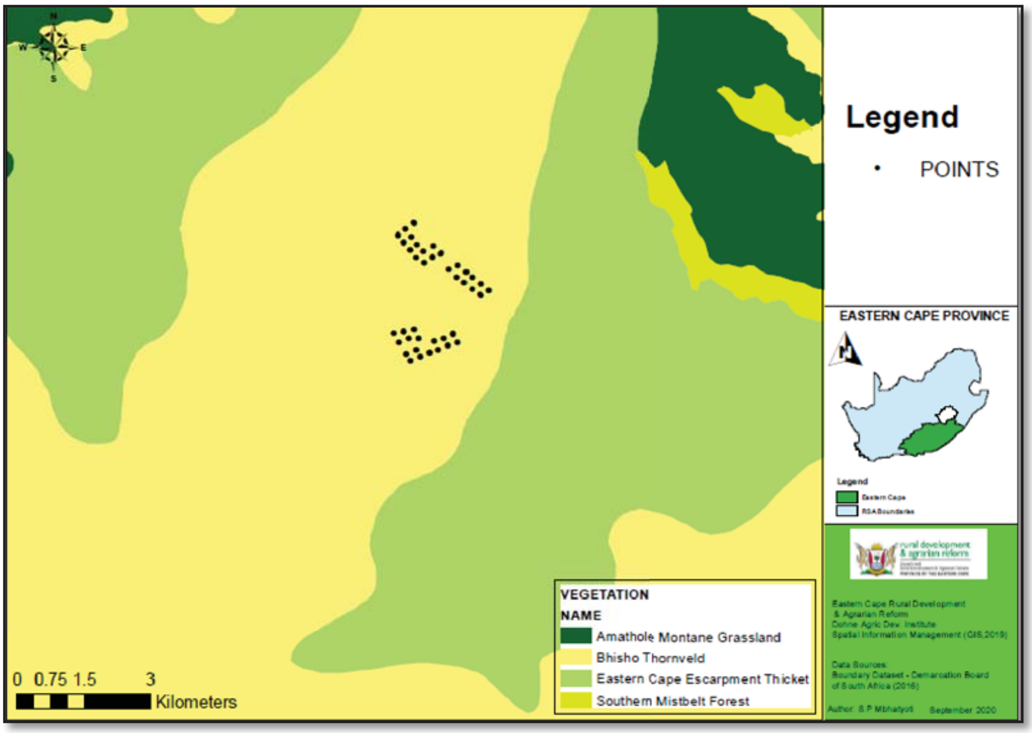



**Figure 6.2: Vegetation types and experimental layout at Krwakrwa Village**

### 6.3.2 Data collection

This study measured rangeland water dynamics in order to determine the potential of a rangeland ecosystem in relation to forage productivity. The rangeland ecosystem's RUE was measured based on the water recharge (run-on and infiltration), capacity to store (soil moisture and water-holding capacity) and discharge rate (evaporation and transpiration).

The major factors, such as the influence of vegetation on rainfall interception and water storage, are, to a larger extent, believed to be influenced by species composition and vegetation cover. Therefore, vegetation cover and species composition were measured seasonally. This would further be influenced by soil texture and landscape characteristics (slope, gradient and aspect). Water use efficiency is more species specific, and therefore the allocation and categorisation of rangeland species into low, moderate and high WUE is empirical and will help to factor WUE when determining rangeland condition and rainwater efficiency.

Figures 6.3 to 6.5 are the trial layouts at three sites in two different veld types in which the study was conducted.

| Rows | C1 | C2 | C3 | C4 | C5 |
|---|---|---|---|---|---|
| 1 | | | | * | * |
| 2 | | | | * | * |
| 3 | | * | | * | |

* Cages where moisture access tubes have been inserted
C Cage numbers

**Figure 6.3: Layout of enclosure cages at the thorntree site, located on the Bhisho thornveld veld type (SVs 7)**

| Rows | C1 | C2 | C3 | C4 | C5 | C6 |
|---|---|---|---|---|---|---|
| 1 | * | * | | | * | |
| 2 | | | * | | * | * |
| 3 | | | | * | * | * |

**Figure 6.4: Layout of enclosure cages at the reservoir, located on the Amathole montane grassland veld type (Gd1, previously known as Dohne sourveld)**

| Rows | C1 | C2 | C3 | C4 | C5 |
|---|---|---|---|---|---|
| 1 | * | * | | | * |
| 2 | | * | * | | * |

**Figure 6.5: Layout of enclosure cages near the chief's residence, located on the Amathole montane grassland veld type (Gd1)**

### 6.3.3 Sampling and analysis process

**Rainfall and evapotranspiration**

Data was collected seasonally, and climatic data (rainfall, temperature and evaporation) was accessed from Google Earth Engine Code. Two scripts were constructed for precipitation and evapotranspiration. Coordinates for all sites were captured in order to feed on the scripts when extracting data from Google Earth Engine Code. Both rainfall and evapotranspiration were collected for 2019, the same year of plant sample collection for biomass. All data from Google Earth Engine Code was downloaded in a *csv format and later stored in a comma-delimited ASCII text format, converted to Excel and grouped into the sum of monthly figures, instead of daily figures, before being analysed.

**Biomass production**

Biomass production samples were collected at the end of each season together with soil samples for a full season (one year). Plant samples were cut using a 0.5 m x 0.5 m (0.25 $m^2$) square quadrat, and samples were cut at 2 cm above ground surface using a pair of scissors. Samples were oven dried at 60 $^oC$ for 48 hours. All samples were weighed before and after oven drying to get wet and dry weights.

**Soil sampling and analysis**

Soil samples were collected using a spade and two samples were collected per sampling site (top sample 20 cm deep and bottom sample 20 cm below the top sample up to 40 cm deep). All soil samples were subjected to laboratory analysis for texture (silt, sand and clay), infiltration rate and soil moisture access. Soil texture was later classified. This would assist in determining soil water-holding potential.

**Species composition**

Belt transects at a 100 m line within each row at each site was measured to determine grass composition using the step-point method along the belt transect (Vetter et al., 2006). A metal rod was lowered every two steps and herbaceous species nearest to the point were identified. In each belt transect, grasses were identified to species level using the method of Trollope et al. (1989). Other herbaceous plant species were also identified and recorded. Grass species were later grouped according to their ecological status: Decreaser species, Increaser I species and Increaser II species using the procedure of Trollope et al. (1989). Grass species were also grouped into annuals and perennials.

**Statistical analysis**

Analysis of variance was used to determine significant treatment effect (SAS 2003) on average biomass production of different sites. When significance was indicated, means were separated using Fisher's least significant difference (LSD) procedure at $P < 0.05$.

## 6.4 RESULTS AND DISCUSSION

### 6.4.1 Species composition and landscape function in the old arable lands at Krwakrwa

After site selection, prior to planting, LFA was conducted. This was done to compare the condition of the old arable lands where legume planting was done with old arable lands that had not been identified for pasture establishment. LFA is a vegetation and landscape monitoring procedure that uses rapidly acquired soil surface indicators to assess the biochemical functioning of landscapes. The LFA method involves randomly selecting the starting point and laying out a transect (i.e. 100 m long in this case) as close as possible to the soil surface, straight and taut directly downslope. To measure the width of patches, a 100 cm tape is used and laid across the transect. In the old land selected for pasture establishment, the landscape was composed of more grass patches (38.9%) and Acacia seedling patches (38.9%). In this old land, the number of bare patches (11.1%) was small, but the magnitude of the individual patches was big. Forb patches constituted about 11% of the measured landscape. In terms of the soil surface indicators, there was moderate rain splash protection and high perennial vegetation cover. The few bare patches that existed showed no signs of cryptogram, which resembled the non-presence of microbial activity in these soils. A bare patch refers to a bare ground or an area that is not covered by any form of vegetation. Bare patches were smooth with very small amounts of decomposed material. In old lands that have not been selected for pasture establishment, the occurrence of *Acacia karroo* seedlings stood at 16.7%, while bare and forb patches constituted about 22.2% and 11.1%, respectively.

**Table 6.1: Percentage of patches occurring in old lands in Krwakrwa**

| | Grass patches (%) | Acacia patches (%) | Forb patches (%) | Bare patches (%) |
|---|---|---|---|---|
| Old lands with legumes | 38.9 | 38.9 | 11.1 | 11.0 |
| Old lands no legumes | 49.7 | 16.7 | 11.1 | 22.2 |

### 6.4.2 Species composition of old arable lands in Krwakrwa

Sixteen grass species were identified when species composition was conducted. Most of the grasses identified are increaser species and perennials. *Hyparrhenia hirta* was the most dominant species, while *Paspalum dilatatum* was the least dominant grass species. Of the introduced species (legumes), none of them were identified during species composition surveys, while *Eragrostis curvula* (introduced grass) was identified and showed common occurrence.

**Table 6.2: Life forms, ecological status, grazing values and occurrence of grasses and forbs in Krwakrwa's old arable lands**

| Species | Life form | Ecological status | Palatability | Occurrence |
|---|---|---|---|---|
| *Hyparrhenia hirta* | Perennial | Increaser II b | Low | Dominant |
| *Paspalum dilatatum* | Perennial | Increaser | Low | Rare |
| *Aristida congesta* | Perennial | Increaser II | Low | Common |
| *Cynodon dactylon* | Perennial | Increaser III | Low | Dominant |

| Species | Life form | Ecological status | Palatability | Occurrence |
|---|---|---|---|---|
| *Digitaria eriantha* | Perennial | Decreaser | High | Common |
| *Eragrostis curvula* | Perennial | Increaser I | Low | Common |
| *Eragrostis plana* | Perennial | Increaser II | Low | Common |
| *Paspalum dilatatum* | Perennial | Increaser | Low | Rare |
| *Sporobolus africanus* | Perennial | Increaser III | Low | Common |
| *Sporobolus fimbriatus* | Perennial | Increaser II | Low | Common |
| *Forbs* | Annual | Increaser II | Low | Common |

### 6.4.3 Dry matter production by various grass-legume mixtures planted in Krwakrwa's old lands

Comparing total dry matter production between pasture types, the following results were found:

- The control (grass only) treatment produced the lowest dry matter.
- *Lespedeza cornuculatus*-planted plots resulted in the highest dry matter production.
- All legume-treated plots produced higher dry matter yield than the control plots.
- Even though there are differences in TDM yield production, these differences were not significant between all the treatments. The non-significant difference between sole grasses and legume-treated plots is suspected to be due to the poor establishment and persistence of forage legumes due to moisture stress.

**Table 6.3: Pasture production (t ha$^{-1}$) in Krwakrwa's old lands area as influenced by pasture type**

| Pasture type | Mean | Standard error |
|---|---|---|
| Grass only plot (control) | 16.05$^{a}$ | 2.097 |
| *Lespedeza cuneata + grass* | 16.93$^{a}$ | 2.097 |
| *Trifolium repens* + grass | 18.47$^{a}$ | 2.097 |
| *Lespedeza cornuculatus + grass* | 18.60$^{a}$ | 2.097 |

Similar lower case superscripts within the same column depict a non-significant difference (P < 0.05) between treatments.

### 6.4.4 Dry matter production in Krwakrwa's old lands over three seasons

The least dry matter was produced during spring, while the highest dry matter was produced during autumn. Dry matter produced during autumn was higher than in the other seasons and the biomass quantity was significant. Overall, dry matter production for the treatment and season interaction was significant.

**Table 6.4: Seasonal pasture production (t ha$^{-1}$) in Krwakrwa's old lands**

| Season | Mean | Standard error |
|---|---|---|
| Spring | 33.98$^{a}$ | 2.05 |
| Summer | 39.78$^{a}$ | 2.05 |
| Autumn | 44.19$^{b}$ | 2.05 |

Similar lower case superscripts within the same column depict a non-significant difference (P < 0.05) between treatments, while different superscripts depict a significant difference.

### 6.4.5 Effect of mechanized basins on the quantity of biomass production of various grass-legume mixtures planted in the old lands

The introduction of mechanized basins resulted in the production of the least dry matter in comparison to the plots where there were no mechanized basins.

**Table 6.5: Pasture production (t ha$^{-1}$) in Krwakrwa's old lands as influenced by cultivation practices**

| RWH&C technology | Mean | Standard error |
|---|---|---|
| No mechanised basins (control) | 19.49$^{a}$ | 2.07 |
| Mechanised basins | 17.89$^{a}$ | 2.07 |

Similar lower case superscripts within the same column depict a non-significant difference ($P < 0.05$) between treatments.

### 6.4.6 Soil texture, infiltration and moisture access on rangelands at Krwakrwa

The results for texture, infiltration rate and soil moisture access are displayed in Table 6.6 to Table 6.8 and indicate that the majority of soils across all sites are sandy loam, followed by sandy clay loam. However, in the reservoir site, 55% of soils were classified as sandy clay loam. Most samples that were collected on topsoil were classified as sandy loam soil, except for three samples, whereas samples that were collected below 20 cm of the topsoil varied between sandy loam and sandy clay loam at the reservoir site. There was no soil classification difference or any variation between topsoil samples and those collected at the bottom, both at the Chief and thorntree sites as all samples were classified as sandy loam.

Infiltration rate across all sites predominantly ranged from 5 to 7 mm h$^{-1}$ on all soil classifications except for one sample at the thorntree site that had an infiltration rate of 9 mm h$^{-1}$. Not all collected samples had both top and bottom samples as some sample sites were not deep enough to collect a second sample due to the rocky soil form i.e. Mispah (see Section 3.2.1).

**Table 6.6: Soil texture, classification, infiltration rate and moisture access at Chief site (open grassland) in Krwakrwa Village**

| Sample | Sand (%) | Clay (%) | Silt (%) | Access moisture (mm) | Infiltration rate (mm h$^{-1}$) | Classification |
|---|---|---|---|---|---|---|
| Row 1: S1 (bottom) | 66 | 3 | 31 | 128 | 7 | Sandy loam |
| Row 1: S1 (top) | 68 | 18 | 14 | 124 | 7 | Sandy loam |
| Row 1: S3 (bottom) | 68 | 2 | 30 | 124 | 7 | Sandy loam |
| Row 1: S3 (top) | 65 | 13 | 22 | 130 | 7 | Sandy loam |
| Row 2: S2 (bottom) | 58 | 16 | 25 | 137 | 5 | Sandy loam |
| Row 2: S3 (bottom) | 72 | 10 | 18 | 116 | 7 | Sandy loam |
| Row 2: S5 (bottom) | 53 | 7 | 40 | 144 | 5 | Sandy loam |
| Row 2: S5 (top) | 76 | 18 | 6 | 108 | 7 | Sandy loam |

**Table 6.7: Soil texture, classification, infiltration rate and moisture access at the thorntree site (savannah) in Krwakrwa Village**

| Sample | Sand (%) | Clay (%) | Silt (%) | Access moisture (mm) | Infiltration rate (mm $h^{-1}$) | Classification |
|---|---|---|---|---|---|---|
| Row 1: S1 (bottom) | 68 | 2 | 28 | 120 | 9 | Sandy loam |
| Row 1: S1 (top) | 63 | 2 | 35 | 132 | 7 | Sandy loam |
| Row 1: S3 (top) | 56 | 2 | 38 | 135 | 7 | Sandy loam |
| Row 3: S2 (top) | 59 | 19 | 22 | 136 | 5 | Sandy loam |
| Row 3: S4 (bottom) | 56 | 2 | 42 | 139 | 7 | Sandy loam |
| Row 1: S5 (top) | 57 | 2 | 41 | 138 | 7 | Sandy loam |

**Table 6.8: Soil texture, classification, infiltration rate and moisture access at the reservoir site (open grassland) in Krwakrwa Village**

| Sample identification | Sand (%) | Clay (%) | Silt (%) | Access moisture (mm) | Infiltration rate (mm $h^{-1}$) | Classification |
|---|---|---|---|---|---|---|
| Row 4: S6 (top) | 52 | 20 | 28 | 146 | 5 | Loam |
| Row 4: S6 (bottom) | 50 | 14 | 36 | 150 | 5 | Loam |
| Row 1: S4 (bottom | 56 | 24 | 19 | 139 | 5 | Sandy clay loam |
| Row 1: S6 (bottom) | 58 | 22 | 19 | 137 | 5 | Sandy clay loam |
| Row 2: S4 (top) | 58 | 20 | 21 | 137 | 5 | Sandy clay loam |
| Row 2: S5 (bottom) | 56 | 22 | 21 | 139 | 5 | Sandy clay loam |
| Row 1: S2 (bottom) | 55 | 19 | 26 | 140 | 5 | Sandy loam |
| Row 2: S1 (top) | 53 | 2 | 45 | 144 | 5 | Sandy loam |
| Row 2: S2 (bottom) | 57 | 17 | 26 | 138 | 5 | Sandy loam |
| Row 3: S5 (bottom) | 62 | 16 | 22 | 133 | 5 | Sandy loam |
| Row 1: S1 (bottom) | 66 | 2 | 32 | 128 | 7 | Sandy loam |
| Row 1: S5 (top) | 64 | 3 | 33 | 131 | 7 | Sandy loam |
| Row 1: S6 (top) | 64 | 3 | 33 | 131 | 7 | Sandy loam |
| Row 2: S1 (bottom) | 60 | 3 | 37 | 135 | 7 | Sandy loam |
| Row 2: S6 (bottom) | 63 | 13 | 24 | 132 | 7 | Sandy loam |
| Row 3: S4 (bottom) | 57 | 2 | 41 | 138 | 7 | Sandy loam |
| Row 4: S4 (bottom) | 55 | 2 | 43 | 140 | 7 | Sandy loam |
| Row 4: S4 (top) | 60 | 3 | 37 | 135 | 7 | Sandy loam |
| Row 4: S5 (top) | 69 | 2 | 29 | 122 | 7 | Sandy loam |
| Row 1: S3 (top) | 48 | 2 | 50 | 151 | 5 | Silt loam |

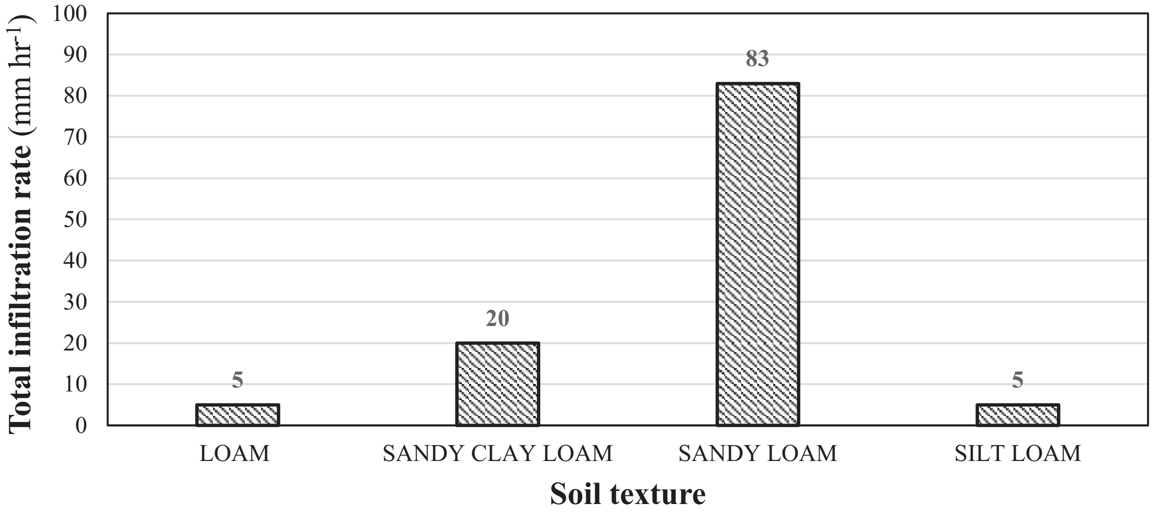



**Figure 6.6: Total infiltration rate per soil classification at Krwakrwa**

Results showed that sandy loam soils had the highest infiltration rate as opposed to silt clay and loam soils. This was due to the fact that the sandy loam soil was more permeable. The high infiltration rates can be attributed to soil physical properties such as particle size, porosity, bulk density and aggregate stability. Results also revealed that there was no major difference in the infiltration rate of silt and loam soils on the rangelands of Krwakrwa.

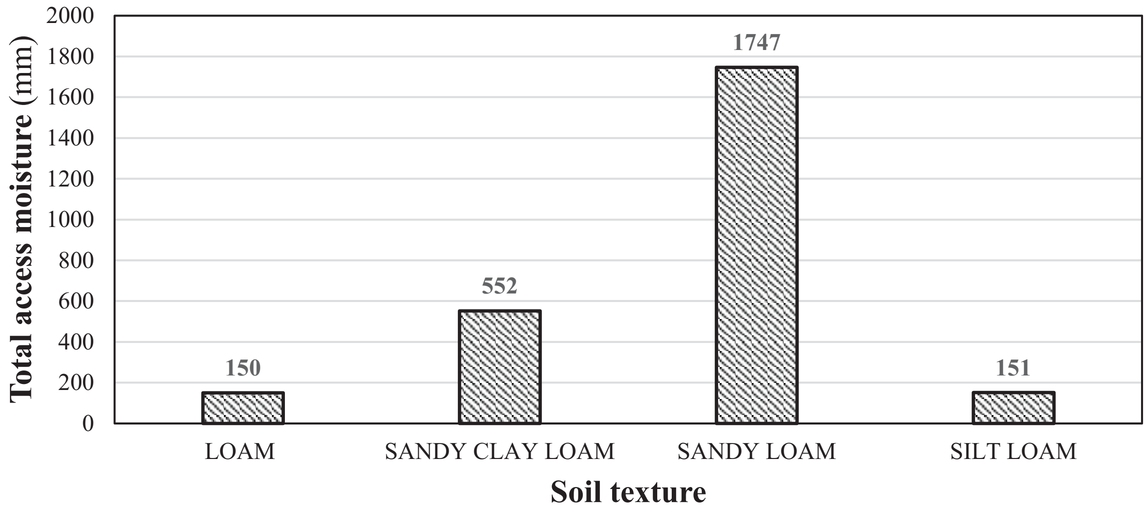



**Figure 6.7: Total access moisture (mm) per soil classification at Krwakrwa**

Sandy loam soils were indicated to have high soil moisture access and retain moisture longer than the other soil classes. Moisture access on rangelands is said to be affected by several factors, such as precipitation, temperature, soil characteristics and vegetation cover. These factors help determine the type of biome present and land suitability. As moisture availability declines, the normal function and growth of plants are disrupted and yields are reduced. As climate changes, moisture becomes more variable.

### 6.4.7 Rainfall

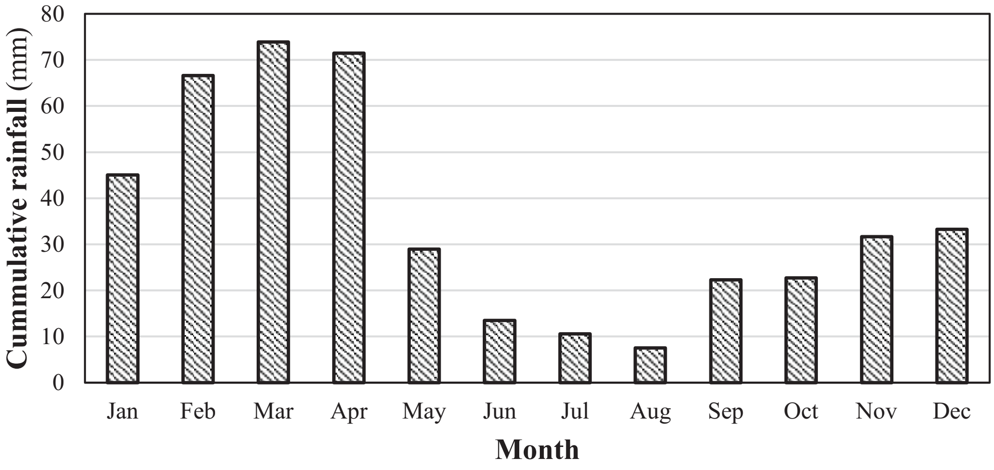



**Figure 6.8: Rainfall patterns for 2019 at Krwakrwa (accessed from MODIS; Google Earth Engine Code)**

During 2019, the highest monthly precipitation was observed during March with a total of 74 mm. Most of the rainfall occurred towards the end of summer and during autumn. During 2019, a prolonged drought spell was experienced with precipitation of below average in spring and later in the following summer. A total of only 110 mm rainfall was measured at the study site from the beginning of September to the end of December 2019. There were 55 rainfall events in 2019, of which 16 events were greater than 10 mm. This pattern of small rainfall events distributed across the season was interspersed by several larger rainfall events, with the single largest rainfall event being 35 mm. The total rainfall of 427 mm for the 2019 seasons was considerably lower than the normal annual mean of 500 to 670 mm (Mucina and Rutherford 2006).

### 6.4.8 Evapotranspiration

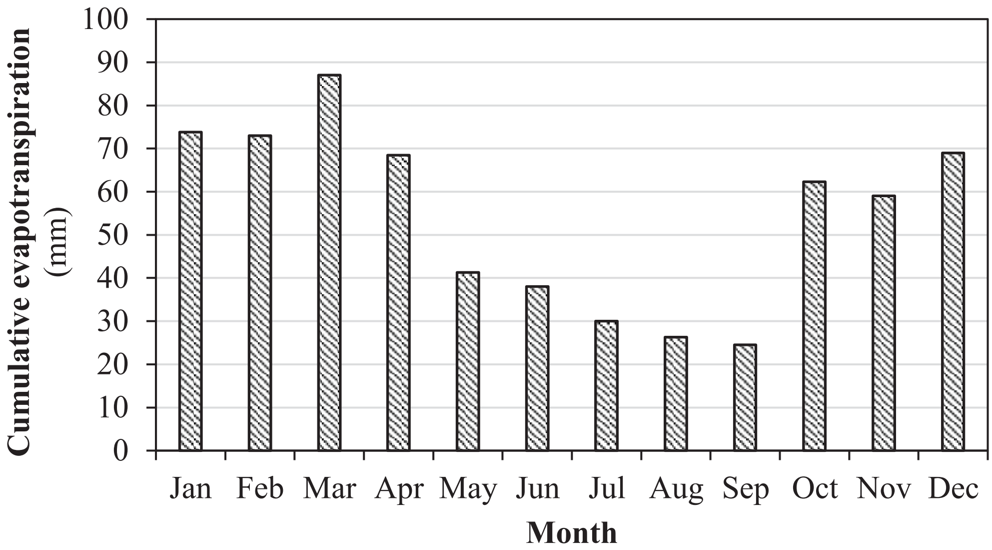



**Figure 6.9: Evapotranspiration at Krwakrwa rangelands in 2019 (accessed from MODIS; Google Earth Engine Code)**

Figure 6.9 provides evapotranspiration rates for various vegetation types at Krwakrwa during 2019. The highest evapotranspiration occurred in autumn at 90 mm and was relatively low in winter as temperatures cooled down. Evapotranspiration was still at lower levels in the growing season (spring) of 2019 as the year was experiencing drought. Evapotranspiration includes evaporation from the soil, water and plant surfaces, and transpiration from plants. About 99% of water taken up by the plant is lost through transpiration. It is the major component of water loss in semi-arid and arid rangelands.

### 6.4.9 Biomass

Table 6.9 to Table 6.11 display the results of biomass production for summer and autumn of 2019 at different sites. The results are interpreted by comparing means to find any significant differences between all treatments. In Table 6.9, where two seasons are compared, the results revealed that biomass production (kg 0.25 $m^2$) differed significantly between, in and outside cages. There was also a notifiable difference in biomass harvested in autumn ($2.03^c \pm 0.110$ in) as opposed to what was harvested in summer ($2.98^a \pm 0.110$ in). Summer biomass was greater than autumn biomass both in and outside. Winter and spring biomass results were unavailable due to lack of enough material to cut (at 2 cm above ground) in both seasons of 2019.

Results from Table 6.10 reveal that there was no significant difference in dry matter harvested inside cages between the thorntree and reservoir sites, and there was a noticeable difference when the two were compared to the Chief site. However, there was a significant difference across all sites when comparing dry matter harvested from outside cages. This illustrates the effects of livestock grazing patterns and distribution as animals at Krwakrwa are free roaming.

There was no significant difference inside cages across all sites in summer. However, a slight difference was observed in autumn at the Chief site ($0.88^c \pm 0.292$) (Table 6.11). Dry matter from outside cages was significantly different on all sites in both autumn and summer, again emphasising the effect of grazing patterns on biomass production.

**Table 6.9: Mean comparison of biomass production (kg 0.25 $m^{-2}$) between summer and autumn at Krwakrwa's rangelands**

| Season | Side | Parameters | |
|---|---|---|---|
| | | Dry (autumn) | Wet (summer) |
| Autumn | In | $2.03^c \pm 0.110$ | $2.43^b \pm 0.145$ |
| Summer | In | $2.98^a \pm 0.110$ | $3.22^a \pm 0.145$ |
| Autumn | Out | $1.72^d \pm 0.110$ | $2.31^b \pm 0.145$ |
| Summer | Out | $2.36^b \pm 0.110$ | $2.66^{ab} \pm 0.145$ |

$^{abcd}$ means in the same column with different superscripts differ significantly (P < 0.05).

**Table 6.10: Biomass production (kg 0.25 $m^{-2}$) at Krwakrwa's rangelands as influenced by location**

| Location | Side | Parameters | |
|---|---|---|---|
| | | Dry | Wet |
| Chief | In | $1.88^{bc} \pm 0.156$ | $2.02^{cd} \pm 0.206$ |
| Reservoir | In | $2.75^a \pm 0.116$ | $3.21^a \pm 0.154$ |
| Thorntree | In | $2.88^a \pm 0.127$ | $3.24^a \pm 0.168$ |
| Chief | Out | $1.61^c \pm 0.156$ | $1.78^d \pm 0.206$ |
| Reservoir | Out | $2.07^b \pm 0.116$ | $2.74^{bc} \pm 0.154$ |
| Thorntree | Out | $2.43^a \pm 0.127$ | $2.93^{ab} \pm 0.168$ |

$^{abcd}$ means in the same column with different superscripts differ significantly (P < 0.05).

**Table 6.11: Biomass production (kg 0.25m$^{-2}$) at Krwakrwa's rangelands as influenced by both season and location**

| Season | Location | Side | Parameters | |
|---|---|---|---|---|
| | | | Wet | Dry |
| Autumn | Chief | In | 0.88$^{c}$ ± 0.292 | 0.880$^{e}$ ± 0.221 |
| | Reservoir | In | 3.32$^{a}$ ± 0.217 | 2.619$^{bc}$ ± 0.164 |
| | Thorntree | In | 3.09$^{a}$ ± 0.238 | 2.604$^{b}$ ± 0.180 |
| Summer | Chief | In | 3.16$^{a}$ ± 0.291 | 2.87$^{ab}$ ± 0.221 |
| | Reservoir | In | 3.10$^{a}$ ± 0.217 | 2.897$^{a}$ ± 0.164 |
| | Thorntree | In | 3.40$^{a}$ ± 0.238 | 3.160$^{a}$ ± 0.180 |
| Autumn | Chief | Out | 0.88$^{c}$ ± 0.291 | 0.880$^{e}$ ± 0.221 |
| | Reservoir | Out | 3.11$^{a}$ ± 0.217 | 2.086$^{d}$ ± 0.164 |
| | Thorntree | Out | 2.92$^{ab}$ ± 0.238 | 2.183$^{c}$ ± 0.180 |
| Summer | Chief | Out | 2.68$^{ab}$ ± 0.292 | 2.344$^{b}$ ± 0.221 |
| | Reservoir | Out | 2.36$^{b}$ ± 0.217 | 2.060$^{d}$ ± 0.164 |
| | Thorntree | Out | 2.95$^{ab}$ ± 0.238 | 2.692$^{bc}$ ± 0.180 |

$^{abcde}$ means in the same column with different superscripts differ significantly (P <0.05).

### 6.4.10 Species composition

Twelve dominant herbaceous species were found across all study sites, which consisted of 11 grass species and forbs (Appendix 7). The composition comprises a range of 51 to 62.6% Increaser II species, 23 to 32.7% Decreaser species and 4.7 to 20% Increaser III species. Of the eight species found in the study area, 50% were of low grazing value, 25% were of moderate grazing value and another 25% were of high grazing value.

## 6.5 SUMMARY

### 6.5.1 Old lands

Legume treatment had no significant effect on forage dry matter yield. In general, it was observed that the grass-legume mixture plots produced more yield in comparison with the grass-only (control) plots, although the difference was not significant. In the current study, greater TDM was measured in the *Lespedeza cuneata* legume plot, whereas the lowest TDM yield was recorded in the control plot. The production of more biomass on grass-legume mixture plots in comparison with the control plots was expected as it had been reported by a number of researchers in grass-legume intercropping studies in the past. Even though grass-legume mixture plots produced higher dry matter yield than the control plots, the difference was not significant at all. This can be attributed to the poor establishment and survival of legumes during the study period as there was prolonged drought during the entire trial period. This finding is in agreement with the study of Sturludottir et al. (2013), which was conducted in Northern Europe and Canada, and reported a higher yield in legume-grass mixtures than in mono-culture treatments. The authors reported that, on average, the legume-grass mixture plots had 9%, 15% and 7% more dry matter than the most productive mono-culture in the first, second and third year, respectively. The attainment of high dry matter yield in the grass-legume mixture plots may be attributed to the beneficial effects of mixing grasses and legumes, and also from the differences in the seasonal growth pattern between the grass and legume species (Luscher et al., 2005), or across years (Nyfeler et al., 2009). The difference in growth patterns of legumes is reported to have potential in leading to the efficient use of resources such as light when grown in a mixture, as opposed to when grown separately. These different functional traits could contribute to positive interactions between species, resulting in higher yields for mixtures in comparison to mono-cultures.

Seasonal change had an effect on dry matter yield production, with the highest dry matter yield recorded in autumn. This can be ascribed to the prolonged dry period, which lasted throughout spring, and minimal rain being experienced during the late summer months. These results concur with the findings of Njoka-Njiru et al. (2006), who reported the attainment of higher and lower dry matter yield during the wet and dry seasons, respectively. The variation in seasonal dry matter production was associated with the phenological development of plants. The reduction of dry matter yield during the dry season can be attributed to the low soil moisture availability for plant growth and the dependence of plants on residual moisture. The implementation of RWH&C techniques in the form of mechanized basins did not significantly affect TDM yield production. Both grass and legume introduction in the Krwakrwa old lands did not bring about a significant change in species composition. Prolonged dry periods throughout the duration of the study can be attributed to the non-significant differences in the TDM yield production of the pastures in Krwakrwa. It must also be noted that, although there was relatively high dry matter production in the old lands at Krwakrwa, the majority of these grasses are of a low palatability status as they are mainly increaser species.

### 6.5.2 Rangelands

Soils significantly affected infiltration and soil moisture. Sandy loam had higher infiltration and moisture access, which was, in turn, viable for plant water use. An evaluation of the changes in several important soil physical properties during the study suggests that multiple processes are contributing to increased water availability, including the absorption of water, increased soil porosity for water storage, and shading to cool and reduce evapotranspiration losses. This was revealed by results from the thorn tree site, where the soil had a better infiltration rate (7 mm $hr^{-1}$), although this was still below the acceptable rate for sandy loam soils (20–30 mm $hr^{-1}$).

The soil's chemical properties were not considered in the study. However, it is stated that the infiltration rate was more sensitive to the sodicity of the soil and to the electrolyte concentration of the applied water than to the permeability of the underlying soil. The mechanical impact of the raindrops and the relative freedom for particle movement at the soil's surface may account for the greater sensitivity of the infiltration rate. These observations suggest that crust formation is due to a physical dispersion of soil aggregates caused by the action of the impact of the raindrops and chemical dispersion, which depends on the soil's exchangeable sodium percentage and the electrolyte concentration of the applied water.

The effect of heavy versus moderate live stocking rates during a season where soils are typically wet depends on the frequency and duration of wet soil conditions. Heavy stocking is detrimental to the physical properties of the soil's surface, and consequently hydrologic condition, especially in heavier textured soils when soil conditions are wet. Research has shown that moderate season-long stocking generally maintains good hydrologic health. Other grazing systems that involve rotations may also maintain good hydrologic condition and benefit key grazing species.

It was concluded that climatic variables need to be considered when measuring rangelands' WUE, as erratic seasonal changes may hugely affect the results. Rainfall distribution throughout the year significantly affected vegetation, with winter and spring resulting in no quantifiable biomass to harvest. The dominance of Increaser II species showed clear signs of overgrazing, and the resilience of decreasers indicated that these species are tolerant to sparse water availability and tolerate grazing, although they disappear where heavy continuous grazing occurs. Decreaser species dominates in well-managed veld, but their proportion declines as selective or continuous grazing worsens. During data collection, uncontrolled veld fires and continuous grazing without resting was observed across all sites. The thorntree site had better species of good grazing value (*Themeda triandra, Digitaria eriantha* and *Sporobolus fimbriatus)* on grazing lands. The over-utilisation of rangeland resources through overgrazing and the exclusion of prescribed burning can accelerate the change of species composition.

Poor veld management practices and climate-related factors such as prolonged drought might influence the species composition. The gradual replacement of palatable grasses is mainly influenced by climate change and poor veld management practices.

The most significant factor facing rangelands is that no uniform set of management guidelines fits all rangeland community types, pastures or other units of grazing land. Plant communities and associated environmental factors are interrelated and multivariate in nature. Interactions among plants, soils, the environment and management are complex.

It was concluded that resting and having moderate grazing reduce evapotranspiration, thus allowing grass to efficiently use water. Shade from shrubs also assisted in the conservation of moisture. This was observed where the thorntree site had high biomass production during all seasons. Species such as *Sporobolus africanus, Eragrostis capensis, Themeda triandra* and *Hyperrhenia hirta* were dominant, even during harsh conditions, and could tolerate low available soil water and high grazing pressure.

# CHAPTER 7: ASSESSMENT OF THE COMMUNAL LIVESTOCK GRAZING PATTERNS, PRODUCTION PERFORMANCE AND LIVESTOCK WATER PRODUCTIVITY IN DIFFERENT SEASONS AND WITH DIFFERENT VEGETATION TYPES

## 7.1 INTRODUCTION

Rangelands are part of an important support system for the livelihoods of millions of people, for livestock production and for biodiversity conservation (Odadi et al., 2018). However, because of climatic and anthropogenic factors, many rangelands are considered severely degraded, impacting negatively on people who rely on land for livestock production (Zhang et al*.,* 2016). Rangeland degradation is mainly associated with poor grazing management and is frequently mentioned as a major contributor to rangeland degradation (Odadi et al*.,* 2017). In areas where rangeland degradation is severe, communal rangelands become the most affected ecosystems. Sustainable grazing management is thus important to improve the value of a rangeland in terms of socioeconomic and ecological systems (Odadi et al., 2017). Statistics in South Africa indicates that communal rangelands make up only 13% of agricultural land. This land is in areas where indigenous people were restricted through the act of colonialism and where land rights were delineated along racial lines through the 1913 Natives Land Act (Samuels et al., 2007). These communal rangelands were managed by the local chiefs or village headmen who determined who could own livestock on the common rangeland or how many heads of livestock were permitted per household and where the livestock should graze at different times of the year. With the implementation of the restrictive legislation after 1913 and the "betterment planning", traditional livestock management governance became fractured. Villages could no longer practise the principles embedded in a herding culture as camps, gates and fences replaced the decisions of herders under whose care livestock had roamed freely and who had been able to select daily grazing areas based on their own preferences (Bailey, 2004).

In communal areas, at the household level, smallholder farmers seldom have the resources to employ a herder for their livestock. However, the loss of herding skills, as well as the recent mandatory school attendance laws, has further eroded the role of herders in determining where livestock should graze in different seasons (Gusha, 2019). Many parts of the former homelands and other dry land regions have been subjected to ploughing, followed by large-scale abandonment, leading to extensive changes in the species composition of the rangeland (Palmer and Ainslie, 2009), favouring more robust, less palatable grasses.

In past years, livestock grazing was managed in a semi-nomadic manner in pastoral rangelands, with frequent changes for pasture regeneration (Ellis and Galvin, 1994). However, land-use practices have changed from nomadic pastoralism to commercial farming, and rangelands that were traditionally managed with animals spread individually, with the presence of herders, is in contrast to sedentary pastoralism where animals are unherded during grazing, but are controlled by fences (Odadi et al., 2018). Veblen et al. (2016) state that, in this system of grazing management, livestock is typically allowed to graze across a general grazing area for a period of time, depending on the available forage and utilisation. They are then moved to a new area to allow for regrowth. Nomadic people use herding to regulate animal movement, while sedentary people use fences to control and move livestock regularly.

Currently, two distinctive grazing management systems have been employed to sustain livestock and manage natural resources: commercial and communal farming systems (Samuels et al., 2007).

The commercial farming system uses a method that adopts rotational grazing management, where camps are grazed for different periods. It is perceived to be ideal for managing livestock (Archer, 2004). The commercial farming system targets a sustained maximum production of livestock products where plants are mostly used for animal forage and livestock is grazed in fenced paddocks and left unattended. Although perceived as productive and beneficial for livestock resource utilisation, this method has shown that resources are selectively grazed where animals may restrict themselves to certain parts of the camp (Baumont et al., 2000). On the other hand, communal rangelands are regarded as completely uncontrolled, as farmers are interested in maximising immediate benefits at the expense of natural resources (Hardin, 1968). This theory maintains that communal farmers are only interested in increased profits, regardless of the impact of the livestock on natural resources. However, Allsopp et al. (2007) argue that it is the effect of too many people concentrated on a small piece of land rather than the traditional grazing management practice that poses a threat to natural resources.

On the other hand, the reality on the ground has changed, where communal farmers have started to recognise the need to manage their common resources. The distribution of livestock in the communal areas of South Africa has not been the subject of many studies, as the technology was not available to determine when and where the animals have been grazing. However, interest in the distribution of livestock grazing has recently become a major concern for livestock managers (Turner et al., 2000), resulting in observations of general grazing behaviour by both human and various automatic recording devices. Living and non-living factors influence the livestock preference of some sites over others, as well as animal behaviour. According to Lyons and Machen (2001), in a free-ranging situation, livestock selectivity is driven by several factors, such as plant type (grass, forbs and shrubs), forage quality, quantity and palatability, plant species composition, shade and shelter, human activities, insects, pests, soil, weather, topography and water. However, in a controlled livestock production system (rotational grazing), graziers are able to control some of these factors in the activity of the livestock through timing and managing the duration of stay in a paddock. It is important to understand livestock grazing distribution in these systems because livestock in natural grazing systems tries to make use of a patchy mosaic of available forage in time and space in order to maximise intake. Understanding this and, importantly, what might limit their ability to do this effectively (such as fencing and lack of water) enables graziers to think about ways to maximise forage utilisation and, potentially, how to improve livestock production.

Studies have been conducted in past years that examine animal location and walking speed (Frost et al., 1997) using GPS monitors. This has rapidly advanced to become a standard method since the mid-1990s. These systems, mounted on neck collars, are used to track the habitat use and behaviour routes of wild ungulates (Schlecht et al., 2004). Dorrough et al. (2004) used GPS technology to track the pasture use of cattle and study the grazing areas of hill sheep. Independent information generated from remote sensing images is used to determine the relationship between vegetation characteristics and animal landscape preferences. The improved developments of GPS technology now make it possible to track free-ranging animals using radio transceivers and positioning data (Tomkin and O'Reagain, 2007).

This study assessed the grazing distribution of cattle under a continuous grazing system using GPS collars to identify patterns of rangeland use where interventions would be most beneficial to improving livestock production. Factors such as vegetation composition were determined to associate with concentration where animals spent a lot of time grazing. The animal’s weight was recorded during collaring to assess livestock performance without herding. The study area was then divided into different territories following Schieltz et al. (2017) to identify where the most grazing occurred since animals can select grazing sites based on nutritional and forage quality preferences to improve their productivity (Lyons and Machen, 2001).

## 7.2 MATERIALS AND METHODS

### 7.2.1 Site description

The study site is located at Krwakrwa Village in Alice, in the central parts of the Eastern Cape. It is in the undulating foot slopes of the Amathole Mountain in the south of Hogsback (centred around 32°44'42 S; 26°54'17 E) at Krwakrwa, which is administered under a communal tenure arrangement (Figure 7.1). The study site comprises two vegetation types: Bhisho thornveld and Amathole montane grassland (Mucina and Rutherford, 2006). The area has a moderately undulating topography, which ranges from steep mountainous escarpments to a moderately rolling mixture of grassland and savannah, sometimes in shallow, incised drainage valleys. Amathole vegetation is characterised by short grassland with high species richness of forbs, and soils are derived on sedimentary rocks of the Beaufort Group (Karoo Supergroup), overlaid by deep, freely drained, highly weathered soils. Weakly developed lithosols are also found in places.

In the Bhisho thornveld, vegetation mainly comprises open savannah characterised by small Acacia trees with a short to medium, dense, sour grassy under canopy of trees (Mucina and Rutherford, 2006), usually dominated by *Themeda triandra* when in good condition. A diversity of other woody species also occurs, often increasing under conditions of overgrazing. Soils in these areas are of mudstone parent material with subordinate sandstone of the Adelaide Subgroup (Beaufort Group, Karoo Supergroup) and is intruded by Karoo dolerite dykes and sills. The substrate is primarily loamy soils, but there is significant variability.

Precipitation of summer rainfall with some rain in winter is common in areas covered by Bhisho thornveld. In the Amathole montane grasslands, rainfall changes the pattern with spring precipitation that peaks in late summer. The mean annual rainfall in this area varies from 500 mm in areas dominated by Bhisho thornveld vegetation to 670 mm in the Amathole montane grasslands (Mucina and Rutherford, 2006).

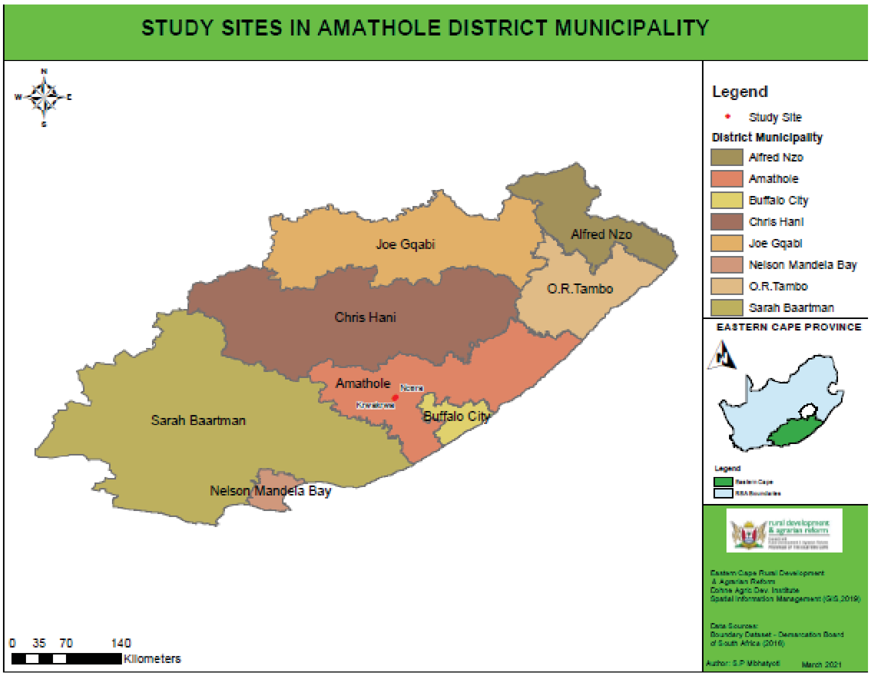



**Figure 7.1: Study site map of the Krwakrwa and Upper Ncera villages**

### 7.2.2 Experimental animals

A social facilitation was conducted at two villages (Krwakrwa and Upper Ncera) where animals would be obtained for conducting research and, subsequent to agreement with community members, an MoU was signed between the parties involved in the research project. The proposed study was also presented to the Dohne Agricultural Research Committee to get approval and ethical clearance to undertake research with live animals. In addition, community collaboration was merged after a workshop with the villagers detailing the nature of the planned interaction with their livestock and the necessary sensitivity to cultural norms associated with livestock handling. This activity was necessary as there are cultural sensitivities regarding women handling livestock in the communal areas. Following approval from both the research committee and the community, two data collection expeditions were conducted during the wet (October to January) and dry seasons (July to September). This followed the same model that was used by Gusha (2019) and Palmer et al. (2015). Thirty-two cattle (*Bos indicus*) were selected from herds of collaborating homesteads and where each homestead offered four animals. One animal per homestead was fitted with a CatLog GPS tracking device inserted into a waterproof collar. Therefore, there were four herds per village, thus 16 animals were selected in each village.

### 7.2.3 Description of the GPS equipment

The CatLog Gen2 recorder is 4.4 x 2.7 x 1.3 cm with a weight of 22 g. It is equipped with a ceramic patch antenna (GPS antenna) with three control status elements: the magnetic switch (to switch it on and off), a micro USB interface (used for charging and communicating with the computer), a status light (green) and a charge light (red). To communicate with the device, an interface serial communication cable and micro USB adapter are connected to a computer's USB port. The CatLog Gen2 device driver and control centre need to be downloaded to communicate with the device. The GPS recorder was set to capture intervals of five minutes to log if no satellite position was available, capture a second reading after a ten-second delay, and log temperature and speed.

The recorder consists of a small chip recorder with an interface for data exchange, a USB charging port and a GPS chipset. The battery capacity is 5,200 mA (runtime approximately 2,160 hours with five-minute intervals) with an accuracy of 5 to 10 m, depending on signal strength (position jitter is expected in low satellite-signal reception conditions). The storage capacity of the equipment is up to 64,000 waypoints. It operates in temperatures between -10 and 50 °C. After downloading, data is exported in a GPX, CSV (Excel) format. The equipment records time, date, position (latitude and longitude coordinates), speed, height and direction.

### 7.2.4 Mounting the GPS on livestock

One animal in each homestead where cattle were selected was fitted with cotton collar belts individually adjusted to their neck size to carry the GPS equipment (Figure 7.2). The devices were inserted in a secure, waterproof pouch attached to a robust neck collar belt. Collar belts were placed on the animals on 17 October 2020 and were retrieved on 18 January 2021 for the wet season. For the dry season, they were fitted in July 2020 and retrieved in September 2020. After retrieving the collars, the position data was extracted from the GPS receiver using the CatLog software.

The data quality varied extremely among collars as only seven collars managed to capture data during the dry season and only one collar was able collect data during the wet season, but was unavailable for analysis. The failure to capture data was attributed to several reasons, such as the GPS's failure to collect data for the whole period, its battery life or the chip malfunctioning due to water contamination.

**Figure 7.2: A GPS collar is fitted to the cattle after weighing an animal at the cattle race in Upper Ncera**

### 7.2.5 Data preparation, cleaning and generating Google Earth images

Data from the GPS collars was downloaded using the CatLog data centre and stored in comma-delimited ASCII text format (*.csv). Data files were randomly renamed without following any sequence. However, data from summer was coded with an "S" at the end of each animal's collar code. All animals were weighed and sexed at the time of collar attachment and this data was stored in a database linked to the collar number. The time stamp on data from the CatLog GPS receivers is in Greenwich Mean Time, and for use in South Africa, the time stamp was changed. Using the runoff packages lubridate and plyr, data from each collar was converted into Central African Time and day/time segments.

The day/time segments for the summer data were 06:00 to 18:00 and described as day and night. The location data from the CatLog GPS receivers is in a geographic projection (latitude and longitude), but as this is a pseudo-projection, it is not possible to calculate area or distance, and conversion to recognised projection is required. In this study, the universal transverse Mercator projection was selected as it is required for further analysis with the Time Local Convex Hull (T-LoCoH) (Dougherty et al., 2018). Once again, this conversion to the universal transverse Mercator projection was undertaken in R using the packages rgdal and sp.

In order to reduce collar failure, all GPS collars had been activated at Dohne prior to installing them on the cattle in the two villages. This meant that all collars contained some data not associated with livestock movement. All these data points were removed by sorting: firstly, by date and time, and removing all data prior to and after actual collar attachment, and also by defining the geographic limits of the village and removing all data points that did not fall within these geographic boundaries. As the CatLog data file also contains a speed estimate, data points that had recorded excessive speeds (more than 5 m sec$^{-1}$) were removed. In this analysis, three cattle at Krwakrwa and four at Upper Ncera were selected from the experimental animals that had full GPS data sets. Google Earth Pro was used to plot livestock distribution movements from the kml files generated by TLoCoH in the study area.

### 7.2.6 Time Local Convex Hull R

T-LoCoH is a package for analysing location data developed in the R system for statistical computation and graphics. It is used to construct home ranges in movement data and to explain spatial-temporal patterns (Lyons et al., 2013). It generalises the non-parametric utilisation construction method and integrates time with space through scaling that relates distance and time in the construction of local hulls in reference to the velocity of the animal.

In both space and time, resulting hulls are local, enabling metrics for multiple dimensions and movement phases of time use, including visitation and duration. As a sample for analysis, TLoCoH produces utilisation distributions with high fidelity to temporal partitions of space by taking hulls rather than individual points, and can differentiate between various behaviours with internal space. T-LoCoH is also used to construct the utilisation distributions from a set of locations by combining minimum convex polygons around each point (Getz and Wilmers, 2004). The T-LoCoH package contains analytical functions for data that have time values attached to them, such as movement data, and can analyse any set of points. However, it has been developed for data collected at regular intervals from a GPS device such as a GPS collar. In each location, time information is used to produce the space used by the animal (Lyons et al., 2013).

### 7.2.7 Vegetation sampling

At the study site, three 100 m transects were laid at each site to determine the herbaceous species composition, which was then assessed using a step-point method as described by Trollope et al. (1989). A hundred individual species were recorded along the 100 m transect at every 1 m interval (Yapi et al., 2018). One herbaceous species at or nearest to the pointer was identified and recorded within the 1 m interval. If the pointer hit the ground, the nearest plant was identified and recorded.

The grass species were grouped into increaser and decreaser species, depending on their response to grazing (Bransby and Tainton, 1977). At the commencement of the trial, the location of transects was systematically allocated at 200 m intervals. Later, recording herbaceous species was allocated using a Google Earth engine that had a pointer in the area where the animals were recorded to be spending most of their time grazing during both the wet and the dry season. Increaser species are divided into three classes: Increaser I, Increaser II and Increaser III, and are indicators of poor rangeland. Increaser I is mostly dominant in under-utilised rangeland and in conditions where little or no herbivory is taking place; they are generally unpalatable. Grass species that dominate in over-utilised rangelands are referred to as Increaser II species, such as sub-climax and pioneer species that produce highly viable seeds and can quickly establish when exposed to the ground. Lastly, Increaser III species are generally unpalatable and increase when selective grazing occurs. They are common in over-utilised rangelands (Yapi et al., 2018). By contrast, decreaser species are an indicator of good rangelands and dominate in rangelands that are optimally grazed. However, they decrease in abundance in over- or under-utilised rangelands. These grass species were further classified according to whether they are perennial or annual grasses, depending on their longevity (Milton, 2004). Perennial grasses can live for more than two years, while annual grasses cannot.

### 7.2.8 Assessing animal live weights for daily weight gains

A group of 16 animals, including eight that were to be collared, were captured on the day of collar installation, weighed using an electrical weighing scale and ear-tagged for identification. Initial weights were recorded as a baseline, and thereafter, animals were weighed twice, once on the day of installing the collars and once on the day the collars were removed to measure daily weight gain for both seasons. The same animals were used as focal animals. The study systematically selected four cattle per homestead as focal animals to measure daily weight gain for performance. The four animals were categorically a cow, a calf, a steer and a heifer. The animals were weighed in the morning before being released into the rangelands for grazing. The average daily gains of the two different seasons were compared in relation to the biomass production and seasonal rainfall to assess performance and water productivity. The daily weight gain of each animal was calculated using the difference between initial and final weight divided by the number of days on feed during collaring. The initial weight referred to the weight of an animal recorded on the day of collaring, while final weight referred to the weight of an animal recorded on the day of removing the GPS collar.

### 7.2.9 Data analysis

All data was analysed using T-LoCoH software in an R environment (Lyons et al., 2013; Lyons, 2014). T-LoCoH initially facilitates the processing of raw position data into the correct time zone (all raw GPS data is collected using Greenwich Mean Time), followed by sorting into daytime and night-time periods. T-LoCoH allows for the conversion of the geographic projection of a GPS system (latitude and longitude) to a universal transverse Mercator projection. This conversion is necessary to correctly calculate distance and area. Using T-LoCoH, the time stamps on the raw data were corrected to Central African Time. Data was cleaned up for GPS positions that did not occur within the study area, or where the speed was more than 3 m $s^{-1}$. These errors mainly arose as the GPS receivers were activated in the laboratory to avoid complications with in-field activation. Poor data points (where the positions had less than three satellites for triangulation) were also deleted from further analysis. All activities that occurred in the areas regarded as rangelands between 08:00 and 18:00 were regarded as grazing. It is acknowledged that livestock undertakes other activities as well, such as drinking, chewing the cud or walking during daylight hours. However, there was no mechanism on the GPS collar to discriminate among these different activities, unless animals seemed to have stood at a drinking point for more than 30 minutes and the GPS collars indicated no movement, and further analysis assumed all animals to be grazing.

## 7.3 RESULTS

### 7.3.1 Dry season cattle movement in the study area

The animals represented here include three cattle from Krwakrwa and four from Upper Ncera (Figure 7.3). They were all mature cows and represented two villages (animals ARC28, ARC29 and ARC31 were from Krwkrwa, while animals ARC08, ARC11, ARC21 and ARC32 were from Upper Ncera). T-LoCoH provided isopleths constructed from hulls that revealed that the animals spent time grazing on 10% (iso level = 0.1) of all recorded points in an extremely small area during the dry season. This is shown by the area in red (Figure 7.3). Although the animals moved to other grazing areas, they did not spend much time there. The edges of the animal distribution that are shown in purple reveal that the animals roamed around the rangelands even though they did not spend much time there.

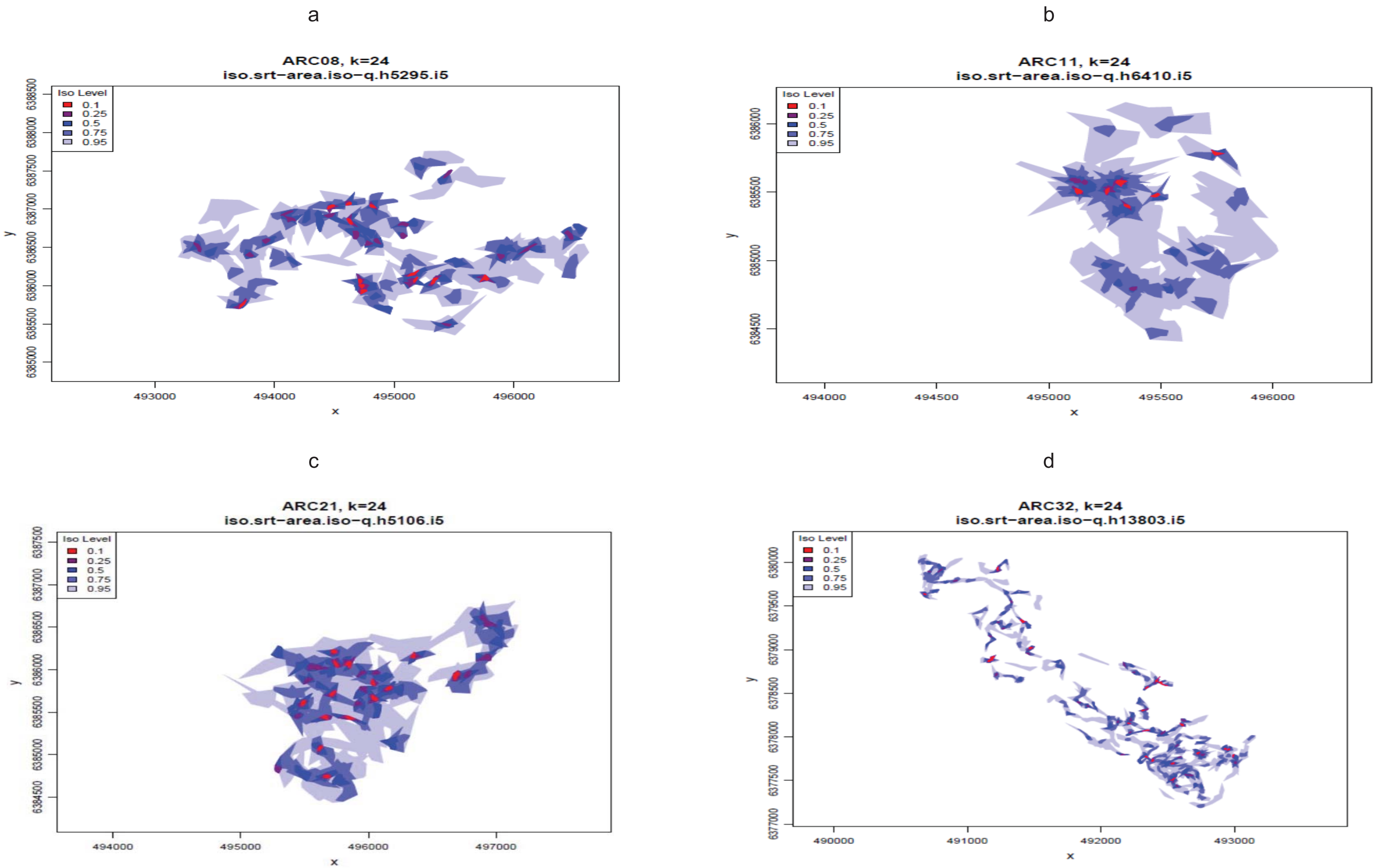



**Figure 7.3: Isopleths constructed in different hulls, sorted by area, indicating proportions of the total points enclosed by four focal cattle during the dry season at Upper Ncera**

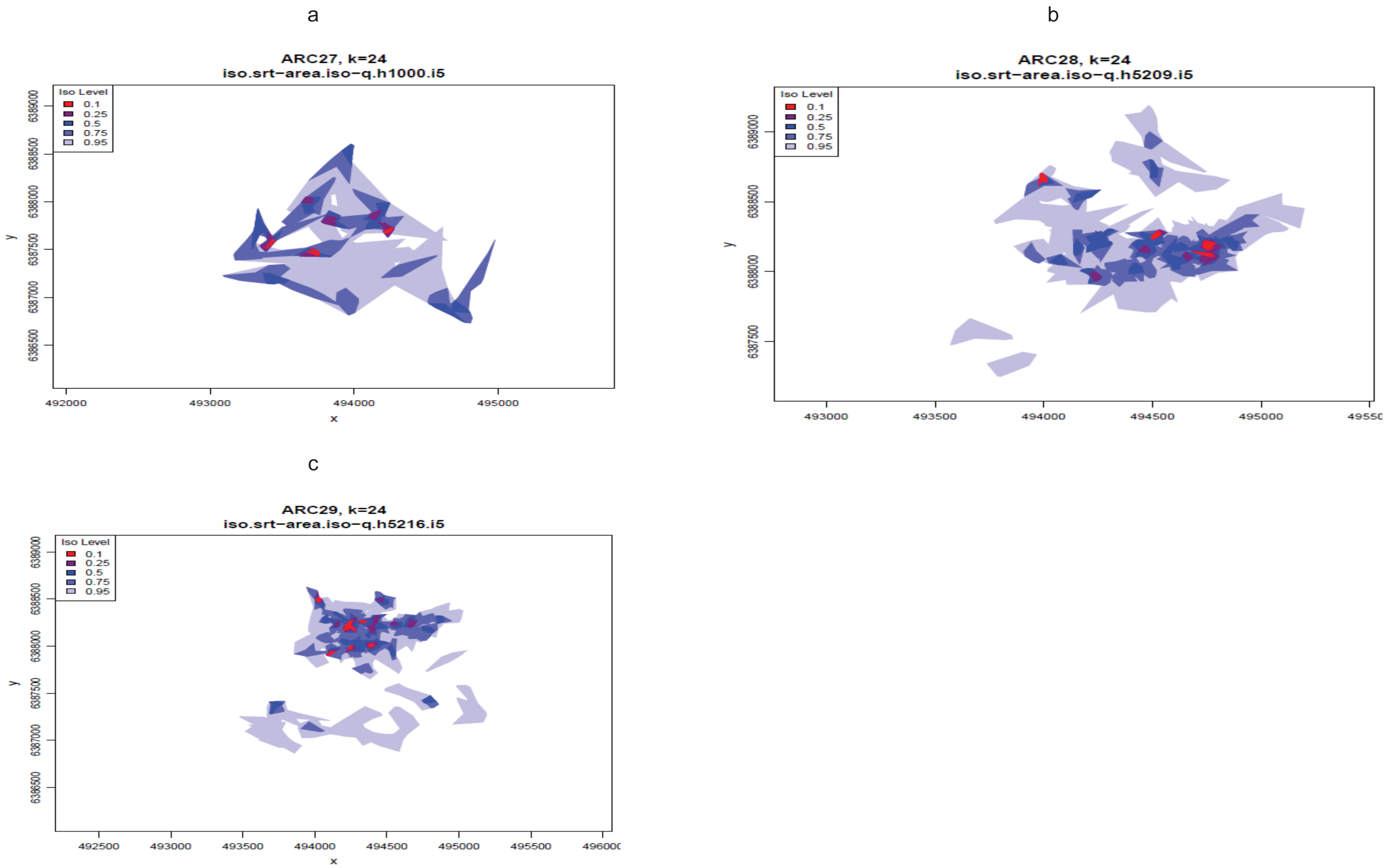



**Figure 7.4: Isopleths constructed in different hulls, sorted by area, indicating proportions of the total points enclosed by three focal cattle during the dry season at Krwakrwa**

### 7.3.2 Wet season cattle movement in the study area

The outputs from the T-LoCoH analysis show isopleths for cattle during the wet season in Upper Ncera. The representative animals included only one cow (ARC32S) grazing during the wet season (Figure 7.5). The outputs from the analysis that provided the isopleths constructed from the hulls revealed that most of the grazing occurred in only 10% of the available grazing area during the wet season. The greatest elongation (red) around the homestead and south-eastern part of the village represents the areas in which most of the grazing occurred. The edges (purple) where the animal moved around were also revealed for the duration of the study, even though the animal did not spend much time grazing there.

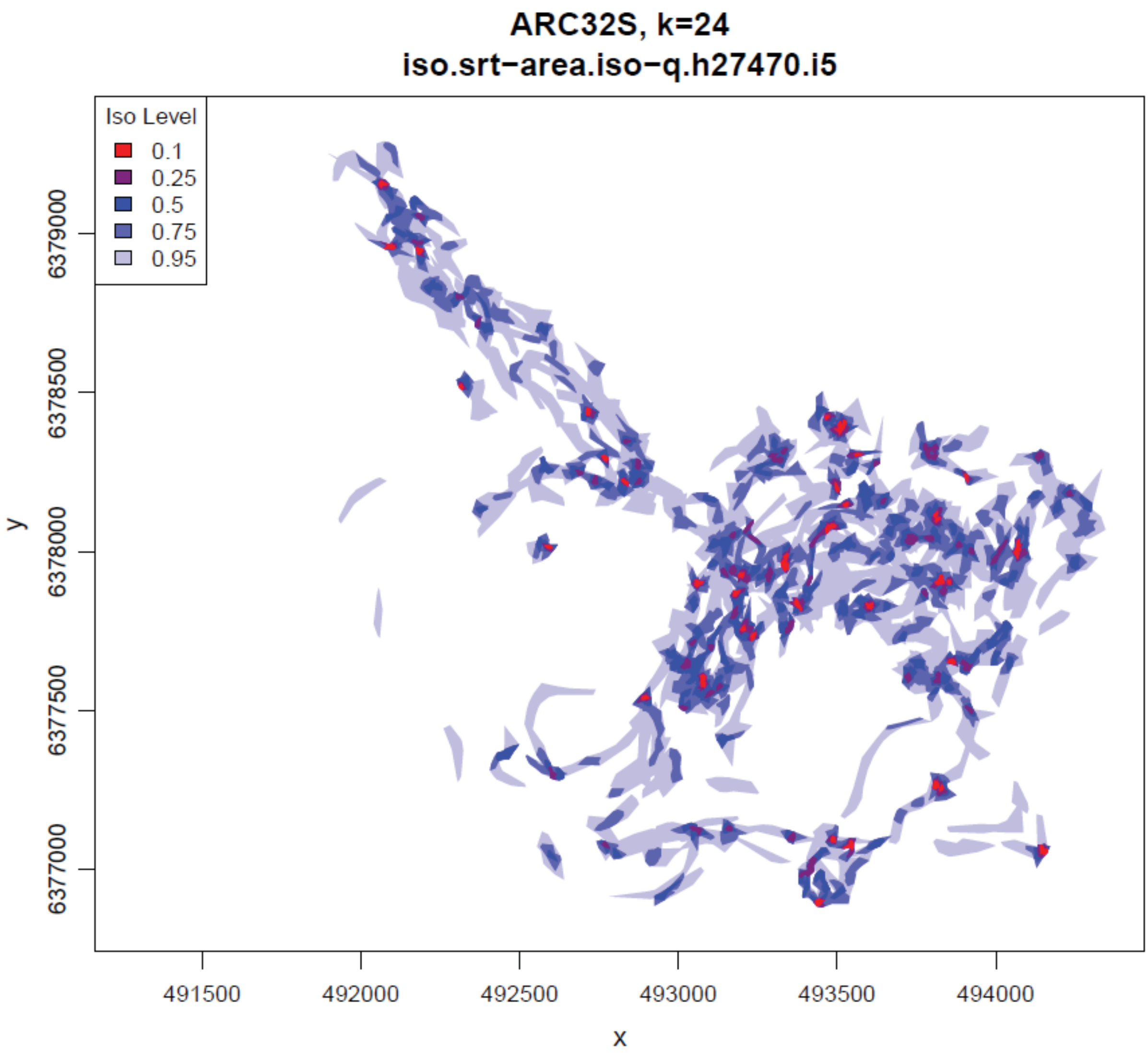



**Figure 7.5: Isopleths constructed in different hulls, sorted by area, indicating proportions of the total points enclosed by one focal cow during the wet season**

### 7.3.3 Google Earth images of cattle grazing during the dry season

The Google Earth image shows the grazing distribution of one cow at Upper Ncera during the dry season (Figure 7.6). Grazing occurred during the day as the night-time points were removed from the analysis.

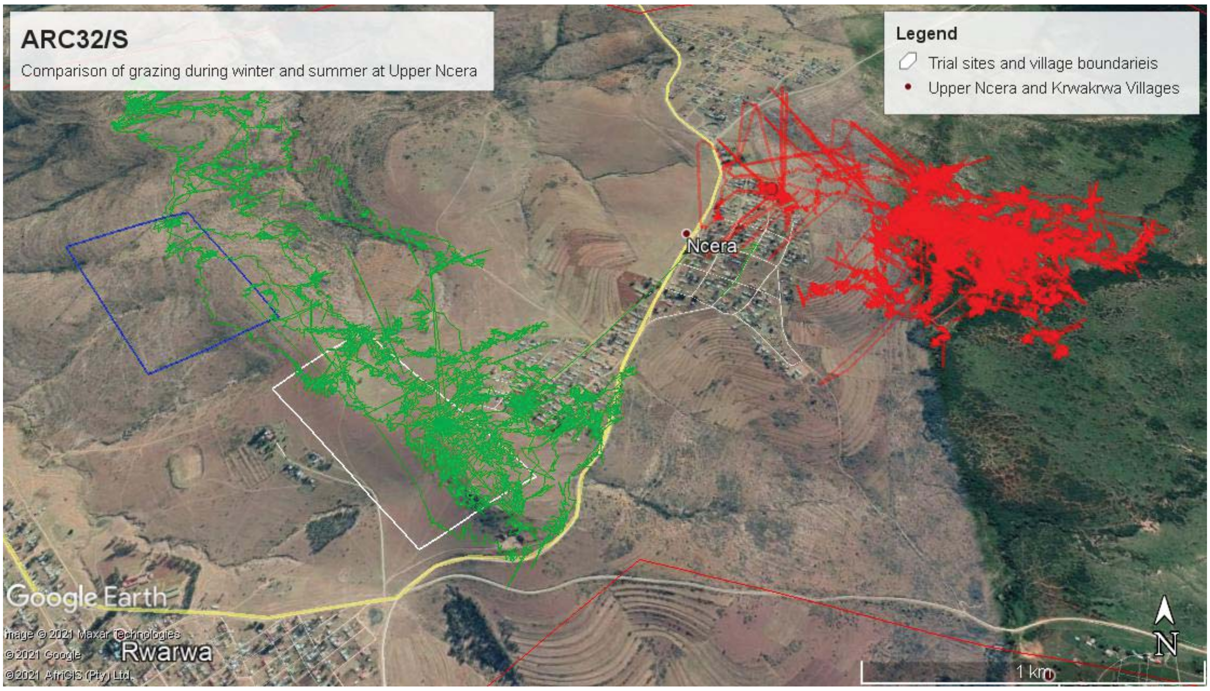



**Figure 7.6: Google Earth plot showing the distribution of one cow grazing during the dry season in Upper Ncera**

### 7.3.4 Google Earth images of cattle grazing during the wet season

The Google Earth image shows the cattle grazing distribution during the wet season in Upper Ncera (Figure 7.7). The image shows areas where the distribution of animals was concentrated.

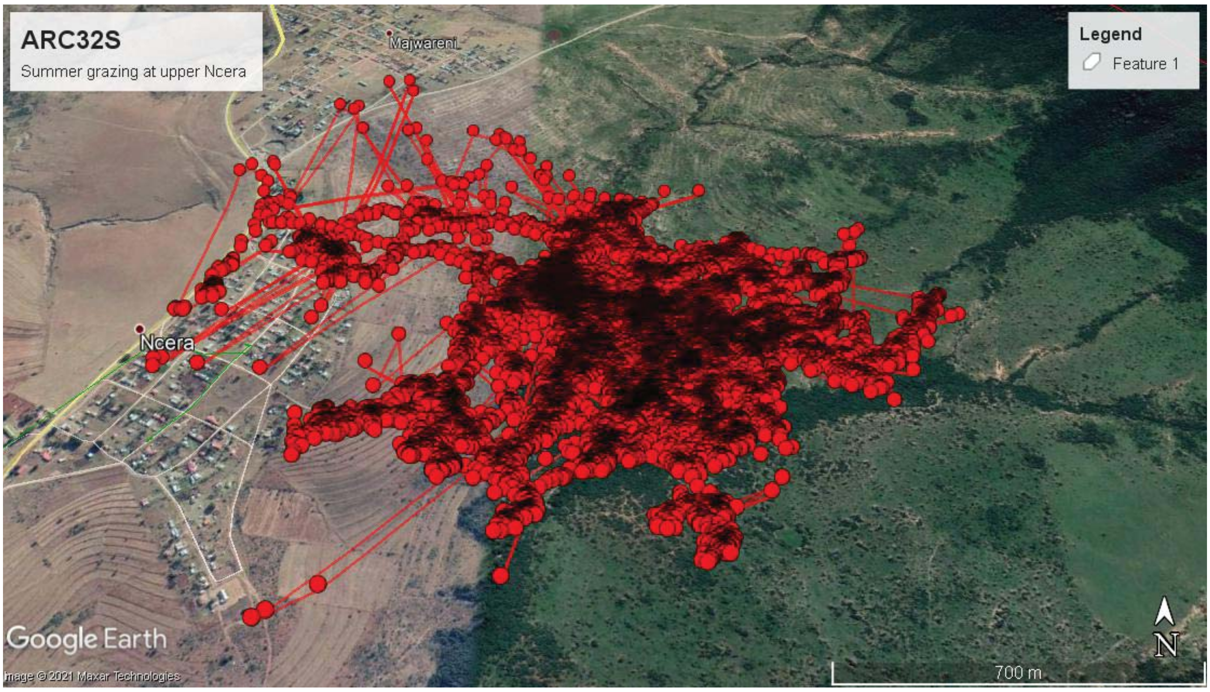



**Figure 7.7: Google Earth plot showing the distribution of one cow grazing during the wet season in Upper Ncera**

### 7.3.5 Vegetation condition and species composition of the areas where livestock grazing occurs

Twelve dominant herbaceous species were found in the study sites, including 11 grass species and forbs (Appendix 7). The composition comprises a range of 51 to 62.6% Increaser II species, 23 to 32.7% Decreaser species and 4.7 to 20% Increaser III species. Of the eight species found in the study area, 50% are of low grazing value, 25% are of moderate grazing value and 25% are of high grazing value. All the species found were perennial grasses except for the forb, which was unknown.

### 7.3.6 Distribution of livestock by number of locations and time

Table 7.1 shows the distribution of the grazing livestock by number of locations, steps taken per day, animal weight gain and area covered during grazing in the wet and dry seasons. There is a difference in the number of locations covered by different grazing livestock in both seasons.

**Table 7.1: Livestock distribution by the number of locations over time during the wet and dry seasons in Krwakrwa**

| Animal type | Number analysed | Total number of locations | Average distance travelled (steps) | Number of locations per day | 10% area covered (ha) | Total number of points used | Total area covered (ha) | Recoding period (days) | Speed (km $hour^{-1}$) | Growth rate (kg $day^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Wet season** | | | | | | | | | | |
| Cattle | ARC04 | 3,911 | 2,600 | 90 | 0.02 | 7347 | 126.69 | 79 | 0.7 | 0.38 |
| **Dry season** | | | | | | | | | | |
| Cattle | ARC04 | 8,513 | 5,200 | 94 | 0.2 | 6,016 | 160.5 | 64 | 2.94 | 0.31 |
| Cattle | ARC07 | 1,741 | 1,500 | 93 | 0.01 | 7,254 | 397.8 | 78 | 0.74 | 0.57 |
| Cattle | ARC10 | 2,900 | 1,500 | 94 | 0.01 | 7,238 | 122.8 | 77 | 0.85 | 0.29 |
| Cattle | ARC07 | 8,734 | 5,200 | 93 | 0.6 | 6,720 | 119.71 | 64 | 0.81 | 1.33 |
| Cattle | ARC10 | 6,242 | 5,800 | 93 | 0.11 | 4,185 | 107.39 | 45 | 0.81 | 0.57 |
| Cattle | ARC18 | 8,659 | 5,300 | 93 | 0.05 | 5,952 | 111.54 | 64 | 1.24 | 0.44 |
| Cattle | ARC19 | 8,850 | 5,300 | 94 | 0.11 | 6,016 | 72.52 | 64 | 0.52 | 0.41 |

## 7.4 DISCUSSION

### 7.4.1 Livestock grazing distribution patterns

Results of the livestock distribution patterns for the wet and dry seasons are presented in several ways and all show that, during the daytime grazing periods, livestock spend a great deal of their time strongly associated with human features. The preparation of hull sets presented for three cattle using T-LoCoH shows that, in both seasons, the animals spend most of their time grazing on 10%, a very small area (1 to 5 ha) near anthropogenic features, for example, homesteads, along roadsides, and in abandoned cultivated lands and riparian zones.

This strong association is due to the active green growth around these areas; even though the grazing resource is very limited, the grass is generally very short and is mainly stoloniferous species such as couch grass (*Cynodon dactylon*) and kikuyu (*Pennisetum clandestinum*) and does not offer much bulk forage (Palmer and Ainslie, 2009). However, livestock is able to "learn the landscape" (Launchbaugh and Howery, 2005) and know that they have to come home, which may be one of the reasons for the strong association with anthropogenic features.

Photosynthetically active green growing grasses generally indicate high-nutrient-enriched sites and are adjacent to stockades and houses, riparian zones and soil conservation structures (Palmer and Ainslie, 2009). These represent the classic grazing lawns of the natural African rangelands (McNaughton, 1985) on which most of the grazing occurs. The presence of these plant species may be facilitated by the combination of high stocking rates and continuous grazing around the homesteads. These patches provide short, green, nutrient-rich grass throughout the year (Ludwig et al., 2005). Continued revisiting to these sites replenishes the nitrogen and other nutrients on a daily basis through dunging and urination. According to Cid and Brizuela (1998), livestock avoids grazing near faeces, but when decomposed and highly nutritious biomass is available later, they will prefer such grazing, resulting in limited grass growth at a later stage. This daily enrichment is similar in nature to the effect of resident indigenous antelope (bontebok, blesbok and black wildebeest) that create and occupy grazing lawns. Although there is limited understanding of the sustainability and dynamic of these lawns, Augustine and McNaughton (2004) show that "periods of positive plant growth following the onset of rains coincide with periods of low nitrogen turnover rates, whereas higher rates occur late in the wet season following plant senescence and throughout the dry season". These higher rates may attract herbivores to stay on these sites, even when the alternative grazing in the natural grasslands may be of a better quality.

More extensive free-range grazing on upland grasslands occurred, but the density of animals was very light. This may be associated with the small livestock numbers, which, according to Stephenson et al. (2016), tend to function as a single unit. Harris et al. (2007) found that small herds usually graze close to one another, and Stephenson et al. (2016) argue that cattle are social animals and tend to associate in groups when grazing and normally behave similarly, moving to watering points, grazing and resting together. The analysis of the information provided on location changes over time; the distance travelled and the speed at which both sheep and cattle move shows that they spend most of their time during the day grazing. According to Schlecht et al. (2004), the speed for resting animals should be zero, high for a moving animal, and low for a grazing animal. In this study, cattle travel in search of grazing because they are not monitored, unlike a study by Odadi et al. (2018), who found that cattle that were monitored travelled a smaller distance in the wet season, so saving energy, which resulted in weight gains. However, in the wet season, both cattle and sheep travelled long distances in search of food and lost weight in the dry season. Odadi and Rubenstein (2015) state that the number of locations covered by an animal looking for grazing during the dry season contributes to weight loss. Lyons and Machen (2001) argue that animals decide where to graze based on their perception and knowledge of consumed plants in the area and their potential choice memory, which later develops a map-like representation of the different areas within the rangeland. The animals have a long-term memory (Lyons & Machen, 2001), which makes them return repeatedly to areas where they previously grazed in search of forage until the forage was exhausted.

### 7.4.2 Factors affecting grazing distribution

Livestock distribution across the landscape suggests that several factors affect how livestock use the landscape as some of the grazing land was not used by free-ranging animals. The factors observed in this study include topography, distance from water and plant composition, and were also found by Lyons and Machen (2001). Another reason for conducting this study was to validate whether animals spend most of the time grazing during the wet and dry seasons.

The study revealed that animals spend most of their time grazing closer to the homestead, watering points and riparian vegetation. According to Bailey (2004), these grazing patterns may reduce stream bank stability, reduce vegetation cover and increase soil erosion. Areas located along the steep slope received less grazing in this study, possibly because the steep slope was far from the watering point and there was no available shade for rest; shade being one of the factors affecting livestock distribution (Bailey, 2004). During the dry season, animals move further in search of grazing if the resource is limited. However, this study revealed the opposite. Possibly, the animals do not move far in search of forage in order to conserve energy. The patterns of animal distribution showed that unrestrained domestic livestock will only move to natural grasslands areas (usually at higher elevation) for short periods during the wet and dry season grazing cycle. Lyons and Machen (2001) state that topography is one of the causes for poor grazing distribution, because cattle prefer flat and gently rolling terrain, such as valley bottoms, level benches and low areas between drainage. The fact that cattle was seen grazing on a steep slope during collaring suggests that they may be unwilling rather than unable to graze on a steeper slope. However, sheep, which are smaller, sure-footed and more agile, can make more use of steeper slopes, but are limited where rugged terrain limits their landscape use (Lyons and Machen, 2001). The collared animals demonstrated that livestock prefer certain grazing sites to others because of the terrain. In addition, roads play a role as the study revealed that animals grazed along the road, which, according to Bailey (2004), enables the animals to travel and graze on the vegetation alongside the road.

Distance to water (the river, in this case) may be a strong motivator of grazing distribution for both cattle and sheep. Water acts as a limitation at which the mechanism for foraging operates. According to Lyons and Machen (2001), livestock needs free access to water for improved production. Distant water sources decrease livestock production efficiency because they use energy to travel from the grazing area to the watering points, thus making availability a major source of poor grazing distribution across the rangeland. However, plants that are near the watering points are heavily grazed, which results in reduced forage production. In their study, in which animals were fitted with GPS collars, Lyons and Machen (2001) found that watering points are the main factor determining the distribution, movement and concentration of grazing animals. Their results reveal that areas that are close to watering points receive more grazing than areas that are far from watering points. Different livestock species have different forage preferences, strongly influencing grazing distribution. Cattle prefer to graze on grasses and tend to avoid bushes, However, sheep prefer short green grass. The species composition also plays a major role in grazing distribution. Although different plants may be found in the rangeland, they receive different grazing pressure because of their chemical composition (Lyons and Machen, 2001). In this study, the most abundant species in the area was *Eragrostis capensis*, a tiny perennial C4 grass that is moderately resistant to continuous grazing. It grows well on the open short grasslands, on young soils or under thorntrees. Although this species tolerates overgrazing because of its strong root production, succession ability, drought tolerance and its ability to compete for resources, it has a low forage value and can result in livestock economic losses (Scheffer-Basso et al., 2016). Another species that was abundant in the study area was *Themeda triandra*, which grows well in grasslands where there is moderate grazing. It can also withstand fire. However, it disappears where soils have been severely disturbed or where continuous overgrazing occurs.

### 7.4.3 Livestock grazing distribution and implications for proper grazing management

The results of livestock grazing distribution and its impacts on species composition call for the development of proper grazing management to monitor livestock movement in communal rangelands. Livestock herding, which improves livestock's technical efficiency, would be ideal if it was introduced as one of the management tools for livestock monitoring in rangeland utilisation. Livestock herding is a process whereby people move livestock in a rangeland from one place to another for even rangeland utilisation. As the fences in the study sites have fallen into disrepair, livestock herding could be a possible way to manage rangelands.

Norton et al. (2013) argue that proper grazing management can improve the grazing distribution of livestock. In this study, animals were not herded, but were left on their own to select their preferred grazing sites. Herding is an effective tool for controlling livestock distribution. In the over-utilised areas of the rangelands, improved grazing distribution could result in an increased stocking rate because of more available forage in the rangeland (Samuels et al., 2007). A herder in communal rangelands could move livestock to different grazing areas for improved, even grazing distribution as the herder purposely relocated animals to alternative sites without harassing them from their preferred sites. The herder should remain with the animals in the rangelands until they get used to the area (Norton et al., 2013). Bailey (2004) states that livestock herding, where people move livestock on horseback from one location to another, has long been recommended as a management tool to modify cattle’s grazing patterns for even utilisation of grass. Although livestock herding is costly, as it needs labour, the over-utilisation of preferred areas such as riparian zones and around the homesteads makes herding necessary to reduce the negative impacts caused by heavy grazing. For improved livestock grazing distribution, rangeland management is often difficult in communal areas because of the topography and annual variation in standing biomass.

## 7.5 CONCLUSIONS AND RECOMMENDATIONS

An analysis of the livestock grazing distribution on the landscape revealed that the animals in Krwakrwa and Upper Ncera spend most of their time grazing around the homesteads, along the streams and near watering points in both the wet and the dry seasons. This grazing habit is linked to repeatedly revisiting areas that are actively green for most of the year. Species grazed had moderate grazing value, which is also a strong motivation for continuous grazing in these areas. An abundance of species such as *Eragrostis capensis*, *Sporobolus africanus* and *Themeda triandra* in the grazing lands neighbouring the homesteads and on the run-on areas and shade in the thorntree rangelands was observed, which animals favoured to other grasses in the open far from home rangelands. Livestock owners or herders need to observe where their animals spend most of their time grazing as the bulk of the rangeland is not used. Extending grazing areas will improve grazing distribution, and improve species composition and forage quality and quantity. It is important to inform owners and herders of the implications of the current grazing distribution pattern for the rangeland condition and for households to have herders who will move livestock into areas that are lightly grazed for even grazing distribution. It is also important to encourage and advise livestock owners to fix their fences and gates so that they can rest some camps during the growing season, allowing the species composition to improve by reducing overgrazing on continuously grazed lands. Alternatively, the local people must elect a committee to oversee the rangeland use.

# CHAPTER 8: BIOGAS PRODUCTION AND APPLICATION OF EFFLUENT AS LIQUID MANURE

## 8.1 INTRODUCTION

The utilisation of renewable sources of energy for electricity and cooking gas has seen tremendous growth worldwide over recent years. It has been encouraged globally because of its availability, but – most importantly – because of its environmental impact. According to Quereshi et al. (2020), renewable energy technologies such as solar, wind, biomass and hydropower, have been adopted in the past decades to reduce pressure on the environment. Phyo (2019) also indicates that, among other renewables, biogas energy is suitable for reducing greenhouse gas emissions through its impact on domestic energy consumption. Similar, Cao et al. (2014), having investigated the energetic, environmental and economic performance of three different household-based modern bio-energy systems, found that greenhouse gas mitigation can be achieved when traditional energy is released with all three systems.

Despite the admirable environment benefits of bio-digesters, their adoption in terms of barriers, and the economic and financial feasibility of the technology, has attracted several studies. Böbner et al. (2019) evaluate the barriers and opportunities of bio-energy adoption, focusing on household biogas in Indonesia. They found that the technology has economic potential in the country if it is adapted to user needs. In addition, policies and business strategies should be designed to achieve energy and monetary savings. Sarker et al. (2020) assessed the economic benefits of biogas systems and barriers in rural household in Bangladesh. The authors found that the economic viability of the technology in the country varies with the size of the system, with bio-digesters greater than 20 $m^3$ not found to be viable. The factors influencing the adoption of bio-digesters were economic, technical, ecological and societal. Salam et al. (2020) had similar findings. The authors stressed that bio-digesters are profitable and almost all the users considered in their study expressed satisfaction with the technology. They identified the household head's level of education, traditional energy cost, income and the amount of available livestock as barriers to adopting the technology.

However, the deployment of bio-digesters as an energy alternative for domestic purposes is on the increase in many developing countries. The technology has become attractive for sustainable rural development schemes considering the high rate of livestock rearing in many rural communities. Like other developing countries, South Africa struggles with rural electrification. In pursuit of greenhouse gas mitigation and reducing pressure on the national grid, bio-energy was identified as one of the renewables for an alternative source of energy (Department of Environmental Affairs, 2016). As a result, many studies have been conducted for the optimal performance of this initiative.

This chapter focuses on the social acceptability and financial and economic feasibility of biogas, also referred to as agricultural waste volarisation for the production of methane. The production of methane (cooking gas) from dung is achieved by employing a bio-digester. This process is relatively inexpensive and requires little or no technical expertise to run and maintain once the bio-digester has been installed. If the system is neglected, however, it becomes very cumbersome to re-establish inoculation and biogas production.

The generation of methane from biomass is an entirely natural process. Depending on the design or configuration, the rate at which the methane is produced might be greater from one biogas digester to another. A typical example is a continuous reactor versus a residential bio-digester. The by-products from digesters are used as fertilizers for plants and may even be made into briquettes and used for the heating of homes.

## 8.2 MOTIVATION

The majority of rural communities, especially those situated in the former self-governing states of Transkei, Bophuthatswana, Venda and Ciskei (TBVC), face a mammoth task with regard to energy sources. They mainly used cattle manure and wood for cooking and lighting, which led to the high rate of deforestation. Nevertheless, since their re-integration into South Africa in 1994, they have had to be included in the electricity supply grid, where the high demand led to load-shedding experienced by the whole country. Due to high rate of unemployment within Krwakrwa and Upper Ncera, biogas was introduced to the villagers.

The primary function of a biogas digester is to convert animal dung, domestic waste, black water or sludge into biogas, which could be used for heating, cooking and the lighting of homes. By this definition, these devices should be deployed outdoors where operating conditions vary significantly from moment to moment and from day to day.

In order to establish a rating for a biogas digester, a set of conditions needs to be defined. This is crucial when determining a fixed rand per volume value for a particular technology. Part of this set of conditions is the ability to feed the biogas digester at least every week in order to maintain the continuous production of biogas, depending on the size of the system.

Maintaining heat in the digester at night and during winter without the use of heat pumps may be achieved by utilising solar radiation during the day. In this case, the biogas digesters are installed underground to shield the methanogens associated with biogas production from large temperature swings.

The by-products obtained after digestion of the substrate are biogas liquid and biogas residue, which are void of any foul smell. The liquid can be used to increase yield in mushroom farming, while the residue is also a good source of organic fertilizer. It is evident that there are both financial and economic benefits to biogas digesters, which will be evaluated in detail in this report.

## 8.3 CONTEXT

Based on a previous study on biogas generation from manure in rural areas of South Africa conducted by Everson et al. (2015), a number of recommendations were made. Based on these, the current project has anticipated a number of issues, including community engagement at various levels, technical operation and maintenance. The two main scenarios raised to stimulate discussion on the topic are the following:

- ***Local government should support and maintain the bio-digesters in an area:***
  This proposition is built on the notion that local government is typically responsible for the support and maintenance of service provision, including electricity and water supply. The delivery of services from a bio-digester, albeit off-grid, is still a service, which the government could provide as an alternative to grid-provided services. If this was the case, it follows that the provider of this "service" would be responsible for its maintenance, and the ability of the system to continue to provide a service.

- ***Households using bio-digesters should pay a monthly fee for the maintenance and support of their bio-digester:***
  If a project was to be funded by an NGO, or even if households were to purchase a bio-digester in their private capacity, it would appear sensible that some form of funded maintenance programme be initiated and sustained. In this scenario, it would seem appropriate that, like any service, a household would be responsible for some form of payment for that service. The suggestion is quite simply that the household should pay a "service contract" to ensure that its installation continues to be operational in the future.

Orchestrating a system of this nature, the actual transferal of funds, and educating a population about its relevance or need, is likely to pose many challenges: gas from a bio-digester system cannot simply be shut off when a household refuses to pay the maintenance bill.

The current project had major issues with exactly this issue, since the operation and maintenance of the bio-digester is expected to be done by the beneficiaries. This chapter therefore attempts to address the financial and economic benefits at the household and societal level.

This chapter addresses the following objectives of the project:

- Demonstrate and evaluate appropriate RWH&C techniques for increased crop and livestock production on homestead gardens, croplands and rangelands with particular attention to biogas from cattle manure as a source of renewable energy and fertilizer at the household and/or village scale for a combination of food and fuel production systems.
- Evaluate the social acceptability and financial and economic feasibility of biogas production to meet energy demands at the household and/or village scale within appropriate institutional arrangements and organisational structures.
- Investigate best management practices of livestock (cattle) for manure collection and transportation to the biogas digesters as a renewable energy source.
- Evaluate the suitability, effectiveness and possible practical application of biogas effluent as a liquid fertilizer.

## 8.4 CONCEPT OF A BIOGAS DIGESTER

A biogas digester (also known as a biogas plant) is a large tank in which biogas is produced through the decomposition or breakdown of organic matter through a process called anaerobic digestion. It is called a digester because organic material is consumed and digested by bacteria to produce biogas. Anaerobic digestion means that this process is taking place in the absence of oxygen.

Biogas is a mixture of gases produced by the breakdown of organic matter in the absence of oxygen and is a renewable energy source. Biogas is produced by anaerobic digestion with methanogens or anaerobic organisms, which digest material inside a closed system, or through the fermentation of biodegradable materials. Figure 8.1 illustrates the concept of a biogas digester where the digestate (decomposed organic material) or bio-slurry is used as a fertilizer in gardens (AGAMA Biogas, 2011).

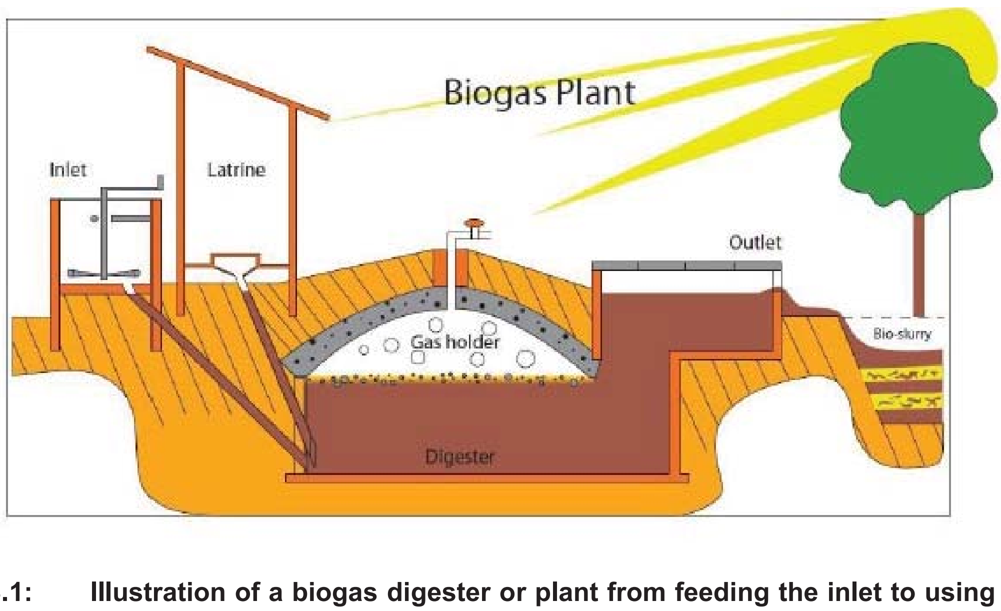



**Figure 8.1: Illustration of a biogas digester or plant from feeding the inlet to using the bio-slurry from the outlet as organic fertilizer**

## 8.5 HOUSEHOLD SUITABILITY REQUIREMENTS

Certain requirements are necessary for a household to be deemed suitable for the installation and running of a bio-digester. In rural areas like Krwakrwa and Upper Ncera, it is common practice to allow cattle to roam freely during the day and be kept in an enclosure (a kraal) near the household at night. Four cows are able to produce 20 kg of dung overnight and are thus able to fulfil the minimum requirement for the purpose of this study (Austin and Blignaut, 2008). The suitability requirements for a household to be deemed technically viable for bio-digester use are as follows:

- They must have four or more heads of cattle that are in a kraal overnight.
- They must be happy to use biogas for cooking purposes.
- They must want to have and use a bio-digester in their household.
- They must be willing and able to provide at least 20 ℓ of water and 20 kg of cow dung every day.
- They must have space in their garden or yard for a digester to be installed.

However, in some instances, homesteads were very active in the upscaling of RWH&C to croplands and rangelands for food production. For this reason, it was agreed that, as long as a household or homestead had access to cattle manure and was active in the other areas of the project, such households or homesteads would be eligible. Appendix 8 presents the questionnaire that was used to determine the social acceptability and technical information required to decide on the financial and economic benefits to a household.

Water is a critical ingredient in the digestion process of the bio-digester system, as well as being a necessity for cooking, drinking and the production of food or fodder. Thus, a water harvesting system is an extended part of this household project, which makes access to the required water feasible in a rural setting. The standalone benefits derived from access to clean water will not be considered expressly, but will be recognised as far as it relates to the running or feeding of the bio-digester.

## 8.6 COST AND BENEFIT OF DIGESTER SYSTEMS

### 8.6.1 Potential cost and benefit

The potential costs and benefits of the project are presented in Table 8.1 and serve to outline some of the costs and benefits associated with a biogas digester system.

**Table 8.1: Costs and benefits of bio-digester systems (adapted from Renwick et al., 2007)**

| | Indicator | Cost | Benefit |
|---|---|---|---|
| Household-level analysis | Financial | • Cost of bio-digester including all materials, labour and installation<br>• Cost of rainwater harvesting system<br>• Cost of biogas utilising equipment (gas burner, etc.)<br>• Repair and maintenance cost of the system | • Cooking fuel saving<br>• Chemical fertilizer saving<br>• Mitigation of health care cost associated with air pollution |
| | Economic | • Cost of extra time used in the adoption of bio-digester use | • Time saving due to biogas and rainwater harvesting (no longer collecting and using more efficient cooking practices) |

| | Indicator | Cost | Benefit |
|---|---|---|---|
| | Economic | | • Increased personal wellbeing as a result of using clean burning energy (reduced respiratory and eye ailments related to poor indoor air quality) |
| **Societal-level analysis** | Financial | • Training and technical assistance<br>• Programme-related costs | • Saving in health-related expenditures (since public funds are likely to be responsible for public health) |
| | Economic | • External costs of bio-digester (related to carbon footprint of construction) | • Greenhouse gas and $CO_2$ reduction<br>• Local environmental benefits (reduced erosion due to reduced overgrazing and reduced deforestation) |

### 8.6.2 Financial cost and benefit

There is a distinct difference between financial and economic costs. Financial costs and benefits are those goods and factors of production that may be traded in the marketplace (Pearce et al., 1989). The material and labour used in the construction of a bio-digester are items that can be bought and sold, and which make up the largest component of financial costs. Financial benefits may include the outputs, biogas and fertilizer that replace items that may previously have been purchased, including fuel for cooking and fertilizer for agriculture (Renwick et al., 2007). The process of valuing these outputs involves the identification of percentage of fuel/fertilizer users, the amount of each product used, the amount purchased versus amount collected of each product, the cost of products and the expected reduction in the product purchased/collected by using the outputs of the bio-digester (Renwick et al., 2007).

### 8.6.3 Economic cost and benefit

Economic costs and benefits include financial costs and benefits, as well as those that relate more to societal values and values that cannot be bought and sold in the marketplace. “In-kind contributions” are material or labour contributions that are made by households and/or communities and are considered economic costs as they “do not involve cash outlays” (Renwick et al., 2007). Time-saving and environmental benefits are not items that may be bought and sold in the marketplace, but translate to benefits and are thus categorised as economic values. One method of calculating the monetary value of time is to value it as the “shadow price” of labour (Austin and Blignaut, 2008). Environmental valuation involves the use of a range of different methods, which will be investigated and selected based on the relevant elements of each environmental factor.

### 8.6.4 Distinction between cost and benefit

The distinction between financial and economic costs and benefits, as well as private (household-level) and public (societal-level) costs and benefits, is important for the decision-making process. From a household perspective, a net private cost or benefit is likely to hold more weight than public (predominantly economic) costs and benefits. In addition to this, the financial aspect of private costs/benefits is likely to be more conclusive for decision makers of households. People are “readily used to the meaning of gains and losses that are expressed in pounds or dollars” (Pearce et al., 1989).

A household is likely to make their decision based not only on expressed monetary value, but also on the direct financial impact that a bio-digester may have on their expendable income. Although economic costs and benefits are arguably as important, they are often values that affect society as a whole and should thus be considered by the government, whose purpose it is to maximise societal welfare (Leiman and Tuomi, 2004). Although economic considerations tend to add significant value, they are often not given the same recognition by households as financial value reflects positively or negatively on stakeholder assets, and may be measured more accurately.

While it is recognised that the end-user of a bio-digester system will be the beneficiary of the financial benefits, it is argued that economic benefits (with the exception of a household's "time-saving") accrue to a greater range of beneficiaries (Renwick et al., 2007). While the end-user and villagers may experience many economic benefits, outsiders may potentially be beneficiaries as well. For example, the establishment of fodder species using RWH techniques may reduce erosion, while using clean-burning biogas may result in a reduction of $CO_2$ emissions and local deforestation, which will potentially benefit society as a whole. Reduced healthcare costs, because of using clean-burning fuels, is also an economic benefit (Austin and Blignaut, 2008). That is likely to assist government and taxpayers responsible for funding healthcare services. It is the purpose of an economist to assess all relevant values "from the standpoint of society as a whole" (Bateman, 1995).

## 8.7 BIOGAS EFFLUENT AS LIQUID FERTILIZER

### 8.7.1 Chemical fertilizers vs. biogas effluent

Chemical fertilizers only increase or replenish a small portion of the required nutrients in the soil. These fertilizers are used to increase crop production. However, by doing so, only mineral fertilizers are added to the soil, without organic manure, resulting in reduced soil productivity. Conversely, organic matter alone may also not result in optimum crop yield. Optimum crop yield and soil fertility levels may be achieved through the combination of chemical and/organic fertilizers. Table 8.2 lists the nutrients available in composted manure, farmyard manure and digested bio-slurry or effluent (SNV, 2011).

**Table 8.2: Range of nutrients available in composted manure, farmyard manure and digested bio-slurry or effluent**

| Nutrients | Composted manure (percentage of dry matter) | Farmyard manure (percentage of dry matter) | Digested slurry (percentage of dry matter) |
|---|---|---|---|
| Nitrogen | 0.5–1.5 | 0.5–1.0 | 1.4–1.8 |
| $P_20_5$ | 0.4–0.8 | 0.5–0.8 | 1.1–2.0 |
| $K_20$ | 0.5–1.9 | 0.5–0.8 | 0.8–1.2 |

### 8.7.2 Financial profitability

The fact that farmers do not realise the importance and potential financial benefit of bio-slurry is not unique to the communities of Krwakrwa and Upper Ncera. In a study by the Centre for Energy Studies Institute of Engineering (2001) in Nepal, it was shown how the financial returns of a biogas plant can be calculated (discounted at the interest rate and measuring the outcome over the 10- to 20-year lifetime of the biogas plant).

The bio-slurry has more specific benefits than those described here (SNV, 2011). The comprehensive bio-digester user survey of 2010 shows that the average family saves US$14 per month on energy, firewood (2,200 kg year$^{-1}$) and kerosene, while over US$50 per year in savings is achieved by replacing chemical fertilizers with bio-slurry (NBP, 2011). In addition, considering both its fertilizer value and the increasing cost of chemical fertilizers, the economic value of slurry is beyond doubt (Sanchez and Gonzalez, 2005).

## 8.8 RESULTS: ELECTRICAL DEMAND AND CONSUMPTION

### 8.8.1 Electrical usage profiles

The electrical usage profiles shown in Figure 8.2 are typical of a rural village supplied by a single 11 kV transmission line. Characteristic of these rural lines is that the voltage drop is significant the further one is down the line from the source. This is detrimental to electrical appliances using a resistive load or heating element. Electrical appliances with starter motors like fridges also tend to have a reduced lifetime due to lower operating voltages (<240 $V_{AC}$).

The purpose of Figure 8.2 is to have a representative usage profile for households or homesteads in Krwakrwa and Upper Ncera. From this profile, there are two distinct peaks, morning and evening, for weekdays, Saturdays and Sundays, and public holidays. The morning peaks are associated with people getting ready for work (kettle, geyser, lights, television), while the evening peaks are associated with people returning from work and preparing for the evening (kettle, geyser, lights, television, cooker or stove). These typical daily profiles were obtained from data collected over a two-year period, at substation level.

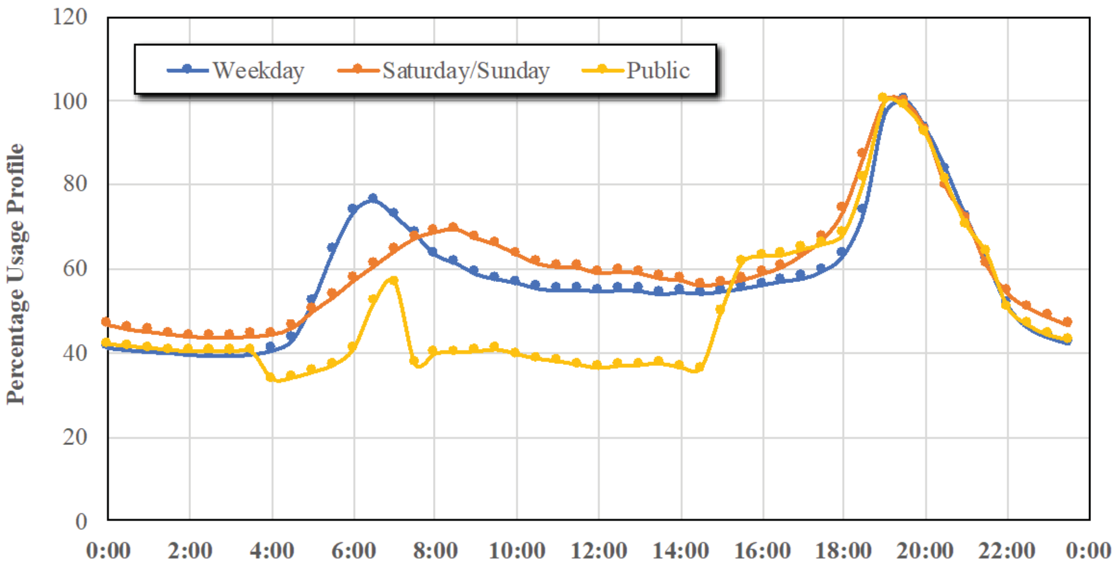



**Figure 8.2: Typical weekday, Saturday and Sunday, and public holiday electricity usage profile for rural Krwakrwa and Upper Ncera**

Of all the household appliances, a two-plate electric stove, rated at 2,000 W, would be the major contributor to the evening peak (Davis et al., 2008). Assuming a reasonable cooking time of 1.5 hours day$^{-1}$, this results in a daily consumption of 3 kWh day$^{-1}$ for cooking (or a demand of 2 kW for 1.5 hours).

### 8.8.2 Household electrical activity associated with cooking

The use of two-plate stoves (normally rated at 2 kW) for cooking is the preferred way of cooking in rural areas when electricity is available at a reasonable cost. However, with continued increases in electricity, it is inevitable that households will consider other sources for cooking. Considering the demand (kW) profile in Figure 8.2 and assuming that cooking takes place during the evening peak, from 17:30 to 19:00, the total energy consumption would be 2 kW x 1.5 hours day$^{-1}$, amounting to 3 kWh day$^{-1}$.

With the free basic electricity of 50 kWh month$^{-1}$, it is easy to see that this will allow for 16 days of cooking. This necessitates the need to purchase additional electricity or consider alternative sources for cooking. Table 8.3 lists typical appliances in a low-income rural household, their rated power and their operating hours (Debnath et al., 2015).

**Table 8.3: List of typical appliances in a low-income rural household, their rated power and their operating hours**

| Appliance | Rated power | Operating hours (h day$^{-1}$) | Consumption (Wh day$^{-1}$) |
|---|---|---|---|
| Lighting (6 x 11 W) | 66 | 4.6 | 303.6 |
| Radio | 11 | 1 | 11 |
| Television | 68 | 2 | 136 |
| Refrigerator | 200 | 12 | 2,400 |
| Cooking | 2,000 | 1.5 | 3,000 |
| **Total demand** | **2,345** | **-** | **5,850.6** |

It is clear that cooking requires 85% of the total demand, while it requires 51% of the daily consumption (Wh day$^{-1}$). Therefore, replacing or at the least reducing the electrical need for cooking can reduce the electricity bill by up to 51%. This would result in a direct financial benefit at the household level and an indirect economic benefit since it will reduce the evening peak demand by up to 85%, thereby reducing the demand from Eskom and thus reducing the probability of load-shedding.

### 8.8.3 Household digester activity required for cooking

To replace the cooking demand of 2,000 W, there was a need to establish whether the digesters installed at Krwakrwa and Upper Ncera have the capability to generate the equivalent of 2,000 W x 1.5 h day$^{-1}$ = 3,000 Wh day$^{-1}$. Following the gas profiles of $CH_4$ and $CO_2$ for the fixed-dome digesters, and considering that 1.0 m$^3$ of $CH_4$ is equivalent to 4.698 kWh of electricity (Khandeparker and Betrabet, 1993), one can consider the cumulative gas production and associated equivalent electrical energy over the 18-day retention period in Figure 8.3. Figure 8.4 shows the scenario where the digester is reloaded on Day 6, when there is just over 0.5 m$^3$ of $CH_4$ in the digester. It is then further reloaded every five days so that the cumulative $CH_4$ never falls below 0.5 m$^3$. From Figure 8.4, it is clear that only the first six days produce sufficient biogas to supply the 3 kWh required for cooking. During this period, it will require 10 kWh to cook for 1.5 hours day$^{-1}$ for six days. This will cost R19.53 at a current cost of 1.9531R kWh$^{-1}$.

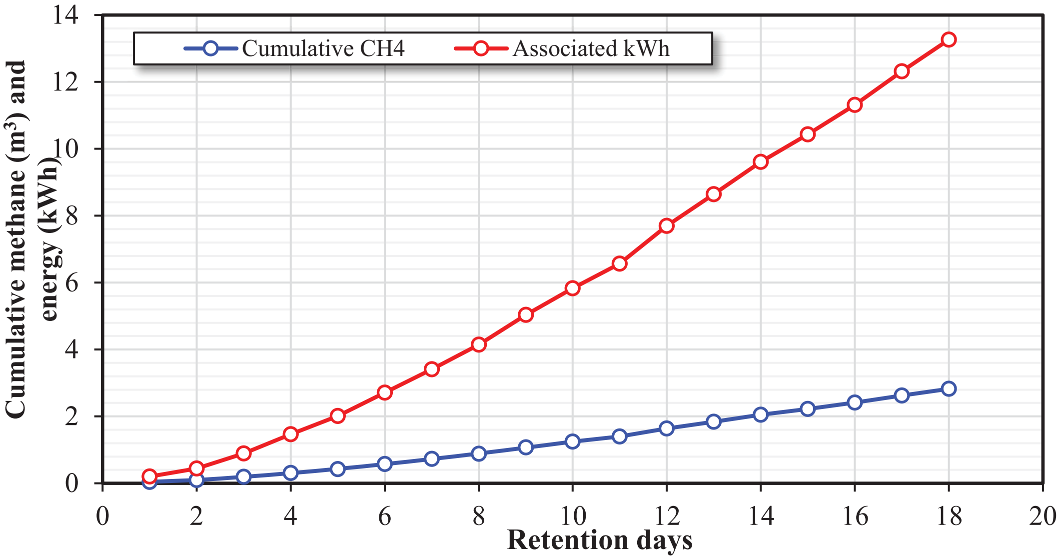



**Figure 8.3: Cumulative gas production and associated equivalent electrical energy**

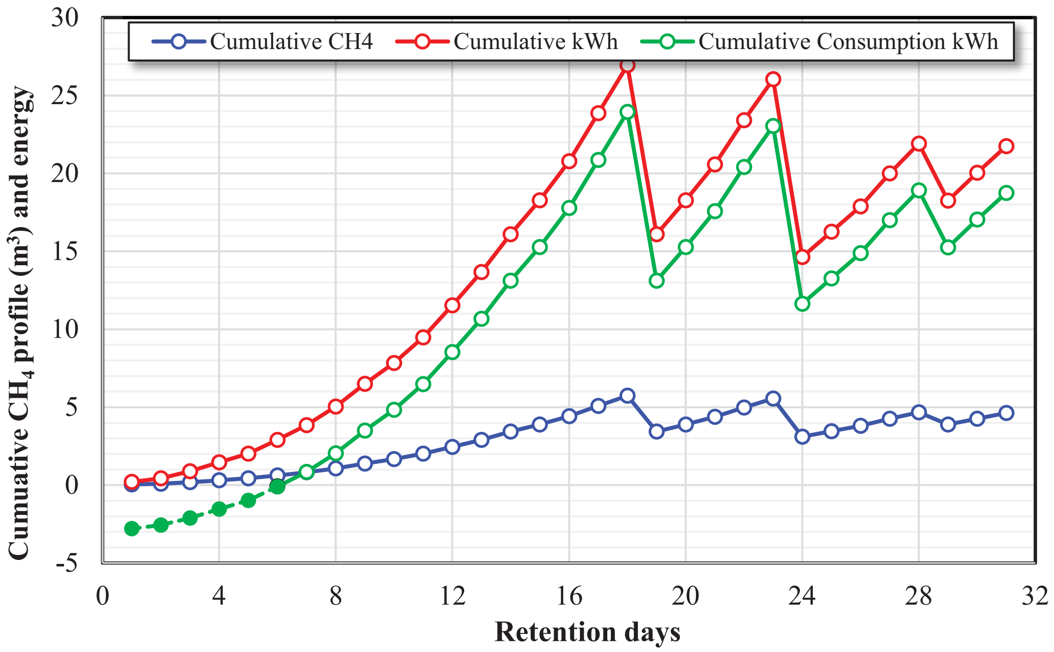



**Figure 8.4: The digester is reloaded on Day 6 and then further reloaded every five days so that the cumulative $CH_4$ never falls below 0.5 $m^3$**

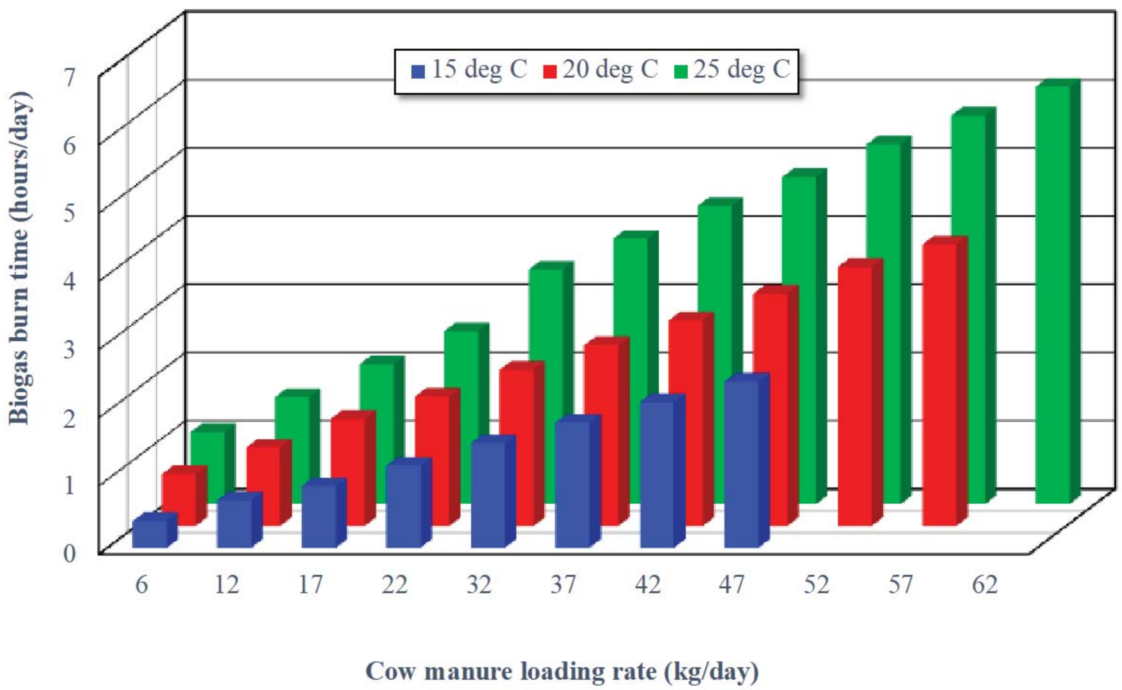



**Figure 8.5: Loading rates for different required cooking times under three different ambient temperatures**

Furthermore, the above scenario uses five days as reloading time. This is, of course, influenced by factors like solar irradiance, ambient temperature, humidity, wind speed and direction, which all influence the microbial activity of a biogas digester. Figure 8.5 (AGAMA Biogas, 2011) suggests loading rates for different required cooking times under three different ambient temperatures.

For the scenario of Figure 8.3, a loading rate of at least 30 kg (6 kg day$^{-1}$, but only every fifth day) was used to have a cooking time of 1.5 hours day$^{-1}$, since the average monthly ambient temperature is always between 10 and 22 $^{o}$C. Figure 8.4 is, however, a simplification of the factors influencing bacterial activity.

## 8.9 RESULTS: FINANCIAL AND ECONOMIC ANALYSIS

### 8.9.1 Potential avoided electrical energy costs

According to Nijaguna (2002), a cow produces 10 kg of dung per day, and 1 kg of cow dung produces 0.036 m$^3$ of biogas. However, in the present study, the volume of the fixed-dome biogas digester is 3.2 m$^3$, and 30 kg of wet dung was fed into the system every fifth day. To form a slurry, a mixing ratio of 1:1 was used, which is around 30 ℓ of water with 30 kg of dung. This quantity of wet dung (60 kg) produced 1.25 m$^3$ of biogas per day on average over the first 18 days. This is assuming that no reloading of the digester took place.

This conservative approach of 1.25 m$^3$ day$^{-1}$ of biogas translates to 5.87 kWh since 1 m$^3$ of biogas is equivalent to 4.698 kWh (Khandeparker and Betrabet, 1993). The local electricity cost in Krwakrwa and Upper Ncera is R1.9531 kWh$^{-1}$, so 5.87 kWh da$^{-1}$y would have cost R11.47 day$^{-1}$. With reloading every fifth day, the total biogas produced per day over a 31-day period is 2.93 m$^3$, translating to 13.77 kWh day$^{-1}$ with an avoided cost of R26.88 day$^{-1}$. Also note that, without reloading, the digester is not able to sustainably generate the required 3 kWh day$^{-1}$ for cooking. Table 8.4 summarises these values for easy comparison.

**Table 8.4: Total cost that can be avoided through the operation of the biogas digester**

| Parameter | Unit | Value | |
|---|---|---|---|
| Retention time | days | 18 | 31 |
| Feedstock | kg five days$^{-1}$ | 0 | 60 |
| Biogas produced | m$^3$ | 1.25 | 2.93 |
| Associated daily energy | kWh day$^{-1}$ | 5.87 | 13.77 |
| Cost at current electricity rate | R day$^{-1}$ | 11.47 | 26.88 |
| **Total avoided costs over retention time** | **R** | **206.46** | **833.43** |

### 8.9.2 Investment of the biogas digester

Table 8.5 outlines the various items constituting the investment of a biogas digester. The prices are for 2017/18 and will need adjustment for future installations. For the current digesters, Table 8.5 is a true reflection of the investment cost. The total investment cost of installing the biogas digester is given here as R17,505.70.

**Table 8.5: Various items constituting the investment of a biogas digester**

| Material used | Quantity | Unit price (R) | Total cost (R) |
|---|---|---|---|
| Cost of fabrication of the biogas digester | 1 | 3,270.21 | 3,270.21 |
| Portland cements (50 kg) | 9 | 84.94 | 764.46 |
| 13 mm concrete stone | 1.2 m$^3$ | 424.77 | 509.72 |
| Grey cement bricks | 1 850 | 2.50 | 4 625.00 |
| All-purpose sand | 1.84 m$^3$ | 311.50 | 573.16 |
| UG rodding eye | 1 | 70.80 | 70.80 |

| Material used | Quantity | Unit price (R) | Total cost (R) |
|---|---|---|---|
| 110 mm PVC pipe | 1 | 141.60 | 141.60 |
| Polyfilla exterior crack filler | 1 | 84.96 | 84.96 |
| Concrete reinforcing mesh | 1 | 354.00 | 354.00 |
| Sealant | 1 | 56.64 | 56.64 |
| Supa lay hold | 1 | 311.52 | 311.52 |
| Brick force rolls | 8 | 19.55 | 156.40 |
| Gas pipe | 1 | 283.37 | 283.37 |
| Others | 1 | 864.26 | 864.24 |
| Labourers | 2 | 2,719.80 | 5,439.60 |
| **Total** | | | **17,505.70** |

### 8.9.3 Economic analysis of the biogas digester

The total investment costs of the biogas digester were calculated based on the techno-economic indicators used for the evaluation. The results are summarised in Table 8.6. The calculated values were obtained using equations 1–10 in Appendix 9.

The total income generated for the project was R15,818.35, while the total investment cost was R17,505.70. The net present value (NPV) is high and positive indicating that the project is indeed financially feasible. This agrees with Du Preez et al. (2013) that a project is accepted if it produces a positive NPV. An investment with a positive NPV would be acceptable, while that with the negative NPV is regarded as unacceptable.

The internal rate of return, which is the rate of interest that generate the NPV, was calculated to be 8%. Based on the internal rate of return decision rule, a project is accepted and can be embarked on if the internal rate of return is above the discount rate (*i*), which is true for the digesters of Krwakrwa and Upper Ncera.

The profitability or return on investment is 64.7%, which compares well to its cost. This shows that the project is acceptable and can be invested in. A payback period of one year and 10 months was calculated as the recovery period at which the expenses used for the project will be recovered.

**Table 8.6: Economic analysis of the fabricated biogas digester**

| Economic indicators | Calculated values (R) |
|---|---|
| Total investment cost | 17,505.70 |
| Total income | 15,818.35 |
| Energy cost per day | 26.88 |
| Cost of maintenance | 4,109.01 |
| Profitability (return on investment) | 64.7% |
| Payback period | 1 year and 10 months |
| Net present value | 22,247.49 |
| Internal rate of return | 8% |
| Annuity | 6,050.75 |
| Cost of annuity | 8,077.11 |

## 8.10 RESULTS: FEASIBILITY

### 8.10.1 Social acceptability of biogas digesters

Although it is an ambitious target to increase the use of biogas as a renewable energy technology in villages, it is increasingly recognised that social acceptance may form a factor constraining the expansion of its implementation and use. It is very important to develop communities, especially in rural areas, and to help them participate in the production of food since this is a global challenge. The development will not have any effect as long as these villagers do not socially acclimatise themselves to change and accept it. That means that, in order to investigate the social acceptance of the use of biogas by the villagers, certain tools, such as a questionnaire, were designed with three groups of questions (background information, awareness of biogas as a renewable energy technology and willingness to invest in biogas production). Indicators used to measure social acceptance included the number of participants making use of biogas, facilitating conditions, cost, trust, place, time for implementation, anxiety, perceived adaptability, perceived enjoyment, perceived sociability, social influence, attitudes towards renewable energy technologies and genuine understanding of the technology.

The social acceptability of this technology, although whole-heartedly accepted at first by the 14 households, still has a long way to go. The reliability, due to the non-compliance of beneficiaries, is questioned by the same beneficiaries.

As the technology matures and institutional arrangements become more symbiotic, the social acceptability will improve. As stated earlier, households want to see direct financial benefits, since biogas digesters are currently seen as cumbersome.

### 8.10.2 Financial feasibility

This situation will soon change when it becomes financially viable to utilise or install a biogas digester because of the prohibitively high cost of electricity, since the cost of Eskom electricity can only increase. All non-renewable power plants must go through the so-called “spiral of death”. Once the cost increases, more customers look for alternative forms of electricity, resulting in the remaining customers having to pay even more. The available data for this project shows unambiguously that biogas digesters are financially feasible and constitute a very good investment.

### 8.10.3 Economic feasibility

This report points out, extensively, the economic benefits of biogas digesters, from the health benefits to the societal and environmental benefits. The economic investment in biogas technology is determined by assessing the benefits to the household or the village as a whole with the larger rollout of the technology, which would be measured through factors such as improved health conditions through improved indoor and outdoor air quality, and more time available due to reduced firewood collection. These benefits would be measured against a set of financing support measures for households to install the technology.

## 8.11 SUMMARY

This chapter aimed to investigate the financial and economic feasibility of rural household bio-digesters with respect to demand-side management. To that effect, households from two different communities were selected for the research. Controlled analysis was conducted. This deals with the leakage test and performance of the bio-digesters due to installation,. Typical meteorological parameters were also continuously monitored. Based on the observed energy usage of individual households, the financial and economic benefits were determined.

The average ambient air temperature in both communities, as determined from the control site, was 19 °C in summer and 12 °C in winter. This is 1 °C below the summer operating temperature of anaerobic digesters and 4 °C above the winter operating temperature.

Furthermore, leakage tests indicate that the above-ground and underground bio-digesters' reactor chambers keep the gas level under severe pressure. The observed energy profile of households indicates a daily cooking energy of 3 kWh. The bio-digester was found to sufficiently generate the gas required for cooking, considering that it is reloaded every five days. This amounted to a daily cumulative energy saving of 13.77 kWh and financial benefits of R26.88. Economic benefits such as profitability, payback period and internal rate of return were 64.7%, one year and 10 months and 8%, respectively.

# CHAPTER 9: CONCLUSIONS AND RECOMMENDATIONS

## 9.1 CONCLUSIONS

Despite many challenges, the project team was able to meet all the objectives of the project. With the collaboration between the project team, relative stakeholders and villagers, it was possible to successfully demonstrate and implement appropriate RWH&C techniques in homestead gardens, croplands and rangelands in order to increase crop and livestock production. Furthermore, bio-digesters were installed for the production of biogas and institutional arrangements were established to improve agricultural production in Krwakrwa and Upper Ncera.

In order to achieve the aim of the project, a research project was conducted in the Eastern Cape. The on-farm study was conducted at Krwakrwa and Upper Ncera, situated on the road between Alice and Hogsback in the Eastern Cape, while the on-station field experiments were conducted at Fort Cox College of Agriculture and Forestry, situated on the road between Alice and King William's Town.

Field demonstrations and experiments were carried out at the homestead gardens, croplands and rangelands in order to do the following:

- Demonstrate and evaluate appropriate RWH&C techniques for increased crop and livestock production in homestead gardens, croplands and rangelands, with particular attention to biogas from cattle manure as a source of renewable energy at the household and/or village scale for a combination of food and fuel production systems
- Evaluate rangeland rainfall use efficiency, water use efficiency and water use productivity, and the use of these parameters to determine rangeland water dynamics
- Assess the communal livestock grazing patterns, production performance and livestock water productivity over different seasons and vegetation types

On-farm demonstrations mainly focused on the following:

- Homestead gardens (RWH&C techniques, crop production and biogas production)
- Rangelands (RWH&C techniques for increased livestock production, rainfall use efficiency, water use efficiency, water use productivity and livestock water productivity)

**Institutional arrangements**

Villagers were assisted with the implementation of workable institutional arrangements to improve production within Krwakrwa and Upper Ncera. Dysfunctional or old institutional arrangements were revitalised, and new and improved ones suggested. The non-adherence and enforcement of these institutional arrangements was problematic, since traditional leadership is not respected and there is too much political interference in these villages. After numerous consultations with relevant stakeholders and villagers, it was agreed that institutional arrangements are critical for the development of these villages. The establishment of committees that have overseen the implementation, and monitoring and evaluation of the institutional arrangements, paved the way for harmonious collaboration and prosperity within these villages. However, the non-functionality of the village committees (e.g. the livestock committee) and poor leadership made the implementation of the workable institutional arrangements difficult. The poor health status of the chief of the area and the ageing headmen further contributed to the poor adoption of the institutional arrangements. The effective implementation and adherence to the institutional arrangements will contribute immensely to the prosperity of rural communities.

**Homestead gardens**

At the homestead gardens of selected beneficiaries, increased crop production with appropriate RWH&C techniques and biogas production was demonstrated. IRWH was implemented and demonstrated in the homestead gardens for the production of a variety of vegetable crops throughout the year. The project also implemented biogas production through the use of both balloon and fixed-dome digesters. The digesters were fed with cattle manure for the production of biogas for cooking. The effluent (bio-slurry) from the digesters was applied as an organic fertilizer in the homestead gardens. Roof water harvesting was implemented and demonstrated, and collected water was mainly used as one of the ingredients for biogas production, for supplemental irrigation for crop production in the homestead garden and for domestic purposes. The villagers received formal and informal hands-on training that enabled them to produce food for household consumption throughout the year by making use of the IRWH crop production technique in combination with supplemental irrigation and bio-slurry application. Records were kept of production, and surpluses were sold to earn an additional income. Homestead gardening is an effective tool to address food insecurity in rural communities.

**Croplands**

The suitability, efficiency and application of bio-slurry as an organic fertilizer for crop production has been evaluated under controlled conditions at Fort Cox College. A statistically laid-out field experiment with 20 treatments and four replications was implemented on the Fort Cox/Valsrivier ecotope. IRWH with soil management practices (mulching and cover crop), in combination with different bio-slurry application rates (0, 3.5, 7 t $ha^{-1}$), was evaluated over four summer growing seasons with maize as the indicator crop. IRWH with a bare soil surface and no bio-slurry application was used as a control treatment. Sound soil management practices proved to be more effective to increase maize yields than bio-slurry application. However, bio-slurry can make a significant contribution to crop yield if sufficient quantities are incorporated into the soil before or with planting. However, it is not practically feasible or economically viable to transport bio-slurry from the bio-digesters at the homesteads to the croplands. Bio-slurry should rather be used in homestead gardens for food production.

**Rangelands**

In the rangelands, increased production was demonstrated by making use of appropriate RWH&C techniques. Legume pastures were established in the old (abandoned) fields to support the community fodder bank. The implementation of RWH&C structures, in the form of mechanised basins in the old lands did not significantly increase grazing capacity, but improved species composition, especially where planted pastures were established with a mixture of legume and grass species. While grass-legume mixtures are climate smart and the most recommended method for improving both the quality and quantity of forage, it must be noted that harsh environmental conditions are a major deterrent to the success of this method. The use of the recommended no-till system for forage legume establishment in the old arable lands also increases the chances of legume non-persistence during unfavourable climatic conditions. The implementation of RWH&C techniques and their positive effect on forage yield production is also directly linked to environmental conditions such as optimum soil moisture availability for plant growth. Best rangeland management practices, like camping and rotational grazing, were established and demonstrated on the natural rangelands to improve species composition and grazing capacity. Veld condition and water use efficiency can be improved by using proper veld management practices.

**Livestock grazing patterns and manure collection**

Animal movement was monitored during a wet and a dry season by fitting GPS tracking devices to collars fitted around the necks of selected animals from the cattle herds in Krwakrwa and Upper Ncera. Livestock normally roams freely in the rangelands on the outskirts of Krwakrwa and Upper Ncera.

There is thus an abundance of low-quality cattle manure in the rangelands that can be used to feed the bio-digesters. Rangelands are located a distance from the villages, meaning that villagers have to walk long distances to collect sufficient manure to feed the bio-digesters. However, where cattle are kraaled at the homesteads at night, fresh wet cattle manure could easily be collected. Villagers who do not have animals were able to collect manure from their neighbour's kraal or from the veld. Although there were no institutions or institutional arrangements regarding the collection of manure and biogas production, the villagers were of the opinion that applicable rules could be implemented and applied by all. The restriction of animal movement by proper camping systems and rotational grazing can improve grazing capacity, and also concentrate manure for easy collection.

**Biogas**

The use of biogas as a renewable energy source in rural villages is an ambitious target. Villagers are not familiar with the biogas technology, so they lack the knowledge and skills to use the bio-digesters effectively to get the maximum benefit from them. Villagers often neglect feeding the bio-digesters or allow them to dry out. It then takes a long time to start them up again and get back to full production. Training on the effective use of bio-digesters is therefore crucial. From biogas gas profiles measured at the University of Fort Hare control site, it was established that the bio-digesters installed at Krwakrwa and Upper Ncera are more than capable of supplying the energy required for cooking, provided that the bio-digesters are continuously fed at least every fifth day. The effective utilisation of bio-digesters will start to take off once the rising electricity cost becomes unaffordable and it is a more financially viable option to use biogas to meet the villagers' daily energy demand.

## 9.2 RECOMMENDATIONS

The project has assisted villagers to realise the potential of improving their rural livelihoods for the better if they work closely together, put workable institutional arrangements in place, adopt suitable RWH&C technologies for crop and livestock production, and use biogas as a renewable energy source. In order to ensure the continued success of the project and widespread adoption of the technologies, a number of recommendations are made.

**Institutional arrangements**

- Every villager should adopt workable and functional institutional arrangements, even though they are not involved in any direct agricultural activities. This will reduce or eradicate any negative contributions by those not directly involved in any type of production.
- Crop and livestock production committees should be elected to oversee the implementation and M&E of institutional arrangements. These committees should be given the authority by traditional and political leadership to enforce these institutional arrangements. Committees should also be allowed to give penalties to those who do not adhere to the institutional arrangements.
- Farmers should be encouraged to join farmers' association since they can play a vital role in their own development. They can be used to manage the frequency of interaction by coordinating the logistics and communication of their members, as well as cost effectively deliver inputs that include training, extension and technology acquisition. Furthermore, they can undertake discussions with the suppliers on behalf of their members to acquire lump sum capital investments in order to increase the farmers' production efficiency.
- Traditional leaders, together with the selected committees, should be given the full power to preside over cases, and the outcomes of such findings should be respected by everyone and implemented based on the judgement.
- Leadership within the villages should be acknowledged and respected.
- Only people who are willing and trustworthy should be elected to leadership positions.
- All government departments should fulfil their mandates as stipulated in the Constitution.

**Roof water harvesting**

- Make use of roof water harvesting to ensure that water is readily available at all times. Collected water can then be used to feed the bio-digesters, for supplemental irrigation and for domestic purposes.
- Implement a tank-training programme to fill the knowledge gap and empower users by providing them with information. Such training should include the reasons why RWH is important, awareness as to why beneficiaries have received the tanks and how the tanks are meant to benefit them if they use them correctly, the potential contamination of rainwater, the health risks involved and how to minimise these, especially if they opt to utilise rainwater for drinking and cooking. An alternative solution may be to train one or two individuals in the village to supervise the functioning, operation, maintenance and repair of the tanks, instead of rolling out a training programme geared at the entire household.
- Certain paints and roofing materials may cause contamination. In particular, lead-based paints must never be used. Tar-based coatings are also not recommended, as they affect the taste of the water. Zinc can also be a source of contamination in some paints, as well as galvanised or corrugated iron roofs. Particularly when new, these surfaces should not be used to collect water for potable use. Roofs painted with acrylic paints may have detergents and other chemicals that dissolve in the runoff. Runoff from fibrous cement roofs should be discarded for the first rain season due to the leaching of lime. Chemically treated timbers and lead flashing should not be used in roof catchments.
- Tanks may be covered and have screen inlets to exclude insects, debris, animals and bird droppings. Almost all steel tanks currently produced for household rainwater collection come with a plastic inner lining to increase the life of the tank, prevent leaks and protect the water quality.
- SABS standards need to be formulated for the development and production of RWH tanks, as well as for the entire process (storage, installation, construction, water treatment and maintenance).

**Homestead production**

- Use suitable RWH&C technologies for food production in homestead gardens and croplands to improve household food security.
- Promote the production of a variety of vegetable crops to give villagers access to a more nutritional diet.
- Incorporate bio-slurry into the soil as an alternative to expensive inorganic fertilizers.
- An integrated pest management programme, consisting of mechanical, chemical and biological methods, should be followed to effectively control weeds, insects and diseases. Villagers and smallholder farmers will have to receive training on the safe and effective use of chemicals.
- Extension services need to provide homestead gardeners with training on all aspects of crop production: soils, seedbed preparation, the implementation of appropriate RWH&C treatments, the planting of various crops, fertilizer application, weed and pest control, harvesting, record-keeping and marketing.

**Cropland production**

- Expand production to unutilised croplands to eradicate hunger and poverty in rural villages.
- Apply sound water and soil management practices (e.g. IRWH and mulching) to minimise unproductive water losses.
- Tractors and other implements should be made available to smallholder farmers so that they can expand their production to the croplands.
- Fencing of all croplands and rangelands is critical to increase productivity in both areas and reduce conflicts. Fencing or improving the fencing on croplands will prevent roaming animals from destroying the crops and RWH&C structures. Fencing on the rangelands will allow smallholder farmers and villagers to implement a rotational grazing system and thereby improve the quality of both their livestock and rangelands.

**Rangeland production**

- Reintroduce camping systems in the rangelands and promote rotational grazing with the aim of restoring palatable grasses.
- Introduce a rangeland vegetation monitoring system to detect changes in plant species composition induced by poor management practices (overgrazing) and/or natural processes (erosion).
- Promote proper pasture management and choice of species that are adapted to frequent water deficits.
- Intercrop planted pastures with legume crops.
- Adopt agronomic procedures (such as minimum tillage, appropriate fertilizer use, improved weed, disease and insect control, timely planting, and a range of rotation options, in conjunction with new adapted cultivars) to improve water use efficiency. This will ensure a reliable supply of sufficient and good-quality forage.
- Provide livestock farmers with training on veld and livestock management, the improvement and rehabilitation of rangelands, record-keeping and marketing.

**Livestock production**

- Restoration and the revamping of dipping tanks is critical for the livestock of smallholder farmers. It will help reduce diseases and stop their spread.
- Livestock should be limited to a certain number per household, or be determined by the carrying capacity of the rangelands. Overstocking will cause overgrazing, which will lead to soil erosion and livestock not having enough food, especially during winter.

**Biogas usage**

- Due to financial constraints, it will be more economically viable and feasible for a number of households to share a bio-digester.
- Workable rules and regulations (institutional arrangements) will have to be put in place to ensure the effective use of the shared bio-digester and its outputs, and avoid unpleasant conflict situations.
- To increase the uptake in the technology, the use of the household digester should be incentivised or at least partially subsidised together with the biogas stove, for instance.
- Inexpensive gas metering could enable gas production and usage to be monitored at municipal level, ensuring that incentives correlate with technology usage. The cost of such incentives should then be weighed against the cost of free basic electricity.

## 9.3 FURTHER RESEARCH AND THE WAY FORWARD

The study has shown that it is possible to use biogas as a renewable energy source at a rural household level. Furthermore, it has shown that it is possible to use the biogas effluent as a fertilizer source. However, more detailed research is needed to support the roll-out of the technology on a larger scale.

The drying and storing of bio-slurry needs to be investigated, so that surplus bio-slurry can be stored to be used in a following growing season. Furthermore, it is necessary to investigate whether the dried bio-slurry can be equally efficient as the fresh liquid bio-slurry. If that proves to be the case, it will be beneficial for community members, since it will be much easier to store and transport the dried bio-slurry than the fresh liquid bio-slurry.

Although two types of bio-digesters (fixed-dome and balloon digesters) were demonstrated for the production of biogas, the efficiency of the various type of digesters used is unknown. Except for these digesters, other types are also available in the market, so a comparative study is needed to identify the most suitable bio-digesters for different scenarios and conditions.

The global energy crisis and striving to mitigate climate change have revolutionised global energy generation. Fuelled by international policies such as the Sustainable Development Goals, specifically SDG 7 (affordable and clean energy), many countries have set at least one renewable energy target (Philibert, 2014). According to the International Energy Agency 2019), approximately 6,000 TWh of solar photovoltaic (PV) energy will be generated in 2050 to supply societal demands. South Africa is actively involved in the global decarbonised and universal energy access consensus as strategised in the National Development Plan (NDP) 2030. In the Integrated Resource Plan (Department of Energy, 2019), the significance of affordable and clean energy in achieving the objectives of the NDP was emphasised. Hence, between 2025 and 2030, a target of 5,670 MW solar PV capacity is set. This is in addition to the existing 1,474 MW and contracted 814 MW (Department of Energy, 2019). A large amount of land will be required to achieve the predicted/targeted solar PV generation, putting food production at risk and bringing about potential food scarcity since the conventional use of land allows for either farming or a solar PV plant on a piece of land. Like farming, the deployment of a large-scale solar PV farm can also negatively influence water (Hernandez et al., 2014). If the conventional land usage is continued, the underlining question is what do we prioritise for the future: food or energy security?

In terms of the dual utilisation of land for agriculture and solar PV power production (an agrivoltaic system), a proposed way forward is therefore as follows:

- Evaluate the tolerance of selected indigenous crops in South Africa under an agrivoltaic system
- Evaluate water retention due to an agrivoltaic system
- Investigate the performance of a solar PV system in an agrivoltaic system relative to local weather conditions and surrounding crops
- Evaluate the economic and environmental benefits of an agrivoltaic system in South Africa

A concept diagram of an agrivoltaic system is presented in Figure 9.1. The typical design of an agrivoltaic system requires tilted PV modules based on local annual solar radiation. The system should make provision for minimum inter-row shading, but should be large enough for agricultural vehicles and machinery. Cultivated crops should be within the maximum height of the stilt and not interfere with the mounting structure and the PV modules (Leon and Ishihara, 2018).

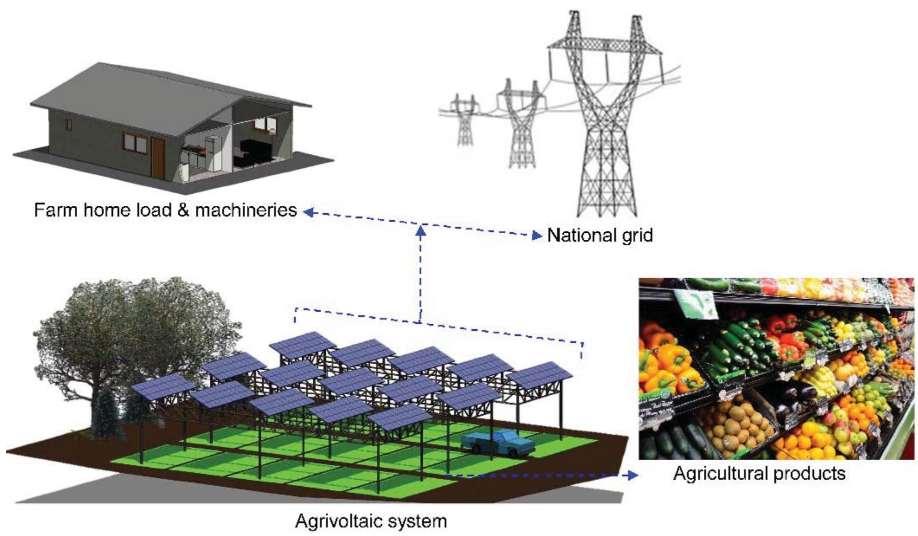



**Figure 9.1: Concept diagram of an agrivoltaic system**

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# APPENDIXES

**Appendix 1: Questionnaire on the socio-economic background, institutional arrangements, energy usage, cropland, rangelands and farming systems of Krwakrwa Village in the Eastern Cape (South Africa)**

**SOCIO-ECONOMIC BACKGROUND, INSTITUTIONAL ARRANGEMENTS, ENERGY USAGE, CROPLAND, RANGELANDS AND FARMING SYSTEMS OF KRWAKRWA VILLAGE IN THE EASTERN CAPE (SOUTH AFRICA)**

WRC Project K5/2495/4

**Instructions**

1. The questionnaire is designed for research purposes only
2. Its intension is to collect baseline data regarding the village involved in this project.
3. Questionnaire administered to the head of household
4. Please make sure that you understand the questions and instructions before you answer.
5. All respondents are requested to provide a true reflection and accurate information as required.
6. Respondents are requested to use an (**X)** when filling in the boxes provided in the questionnaire.

**GENERAL INFORMATION**

Questionnaire No:

**RESPONDENT**:

Name:

Surname:

Contact phone number:

Village name:

Date:

**A. RESPONDENT DEMOGRAPHICS**

**A1** Are you the head of the household?

| | |
|---|---|
| Yes | |
| No | |

**A2** If not, what is the relationship of interviewee to the household head?

| | |
|---|---|
| Wife | |
| Husband | |

| | |
|---|---|
| Sister | |
| Brother | |
| Son | |
| Daughter | |
| Other | |

**A3** Gender of respondent

| | |
|---|---|
| Male | |
| Female | |

**A4** Marital status

| | |
|---|---|
| Single | |
| Married | |
| Divorced | |
| Widow/widower | |

**A5** Age

| | |
|---|---|
| 0–15 years | |
| 16–35 years | |
| 36–65 years | |
| 65+ years | |

**A6** Level of education

| | |
|---|---|
| No education | |
| Grade 6 | |
| Grade 7–9 | |
| Grade 10–12 | |
| Post-matric | |

**A7** Household size

| | Adults (≥16) | Children (<16) |
|---|---|---|
| Male | | |
| Female | | |

**A8** Is the household head a full-time farmer?

| | |
|---|---|
| Yes | |
| No | |

**A9** If not, what is he or she doing except farming?

| | |
|---|---|
| Full-time employed | |
| Seeking a job | |
| Pensioner | |
| Self-employed | |
| Part-time employed | |
| Discouraged worker seek | |
| Child <16 years | |
| Other (specify) | |

**A10** What is the dominant language spoken?

| | |
|---|---|
| isiXhosa | |
| isiZulu | |
| English | |
| Afrikaans | |
| Other | |

**B. SOCIO-ECONOMIC STATUS**

**B1** What are your current sources of food? *(Rank 1 as the most important source of food and others follow in order of importance up to 5)*

| | |
|---|---|
| Purchased food | |
| Own produce (farming) | |
| Food from friends/relatives | |
| Loan sharks | |
| Other (specify | |

**B2** As family, how many meals do you have per day?

| | |
|---|---|
| Once | |
| Twice | |
| Three times | |
| Other (specify) | |

**B3** When do you experience food shortages?

| | |
|---|---|
| January to March | |
| April to June | |
| July to September | |
| October to December | |
| Other | |

**B4** On average how much do you spend on food per month?

| | |
|---|---|
| <R400 | |
| R401–R1,000 | |
| R1,001–R1,500 | |
| R1,501–R2,000 | |
| >R2,000 | |

**B5** What is your current employment status?

| | |
|---|---|
| Permanently employed | |
| Unemployed | |
| Self employed | |
| Seasonally employed | |
| Other (specify) | |

**B6** What is the employment status of other household members?

| | Yes (working) | No (not working) |
|---|---|---|
| Member 1 | | |
| Member 2 | | |
| Member 3 | | |
| Member 5 | | |
| Member 5 | | |

**B7** Do you or any of household member receive any grants?

| | |
|---|---|
| Yes | |
| No | |

**B8 I**f yes, indicate type:

| | |
|---|---|
| Older Persons' Grant | |
| Child Support Grant | |
| Foster Care Grant | |
| Disability Grant | |
| Other | |

**B9** Any other sources of income received by your household?

| | |
|---|---|
| Wages | |
| Remittances | |
| Self-employment | |
| Other | |

**B10** What is average total household income per month?

| | |
|---|---|
| <R1,500 | |
| R1,501–R5,000 | |
| R5,001–R10,000 | |
| >R10,000 | |

**B11** Where do you mostly spend the household income? *(Rank 1 as the most important source of food and others follow in order of importance up to 5)*

| | |
|---|---|
| Food | |
| Education | |
| Health | |
| Clothing | |
| Farming | |

## C. HOUSEHOLD SERVICES

**C1** Do you have access to clean water?

| | |
|---|---|
| Yes | |
| No | |

**C2** If yes, where do you get water?

| | |
|---|---|
| Taps | |
| Rivers | |
| Dam | |
| Other | |

**C3** Do you access water inside your house?

| | |
|---|---|
| Yes | |
| No | |

**C4** Do you have any house with corrugated roof top(s)?

| | |
|---|---|
| Yes | |
| No | |

**C5** If yes, how many houses?

| | |
|---|---|
| One | |
| Two | |
| Three | |
| Other | |

**C6** Do you have access to clinic or any health facility?

| | |
|---|---|
| Yes | |
| No | |

**C7** If yes, how far?

| | |
|---|---|
| >1 km | |
| 1–2 km | |
| 2–4 km | |
| >4 km | |

**C8** What type of structure?

| | |
|---|---|
| Permanent structure | |
| Mobile clinic | |
| Other (specify) | |

**C9** Do you have access to educational facilities?

| | |
|---|---|
| Yes | |
| No | |

**C10** If yes, what is the radius?

| | |
|---|---|
| >1 km | |
| 1–2 km | |
| 2–4 km | |
| >4 km | |

**C11** Do you have access to roads?

| | |
|---|---|
| Yes | |
| No | |

**C12** If yes, what type of roads?

| | |
|---|---|
| Gravel | |
| Tarred | |
| Other (specify) | |

**C13** Do you have access to any source of energy?

| | |
|---|---|
| Electricity | |

| | |
|---|---|
| Gas | |
| Paraffin | |
| Wood | |

**C14** If yes, what energy source do you use for lighting?

| | |
|---|---|
| Electricity | |
| Gas | |
| Paraffin | |
| Wood | |

**C15** What energy source do you use for cooking?

| | |
|---|---|
| Electricity | |
| Gas | |
| Paraffin | |
| Wood | |

**C16** How much do you spend on your energy source per month?

| | |
|---|---|
| R0–R300 | |
| R300–R600 | |
| R600–R900 | |
| >R900 | |

## D. HOUSEHOLD AGRICULTURE ASSET BASE AND FARMING SYSTEMS

**D1** Which of the following resources do your household members have?

| | |
|---|---|
| Homestead garden | |
| Arable land (field) | |
| Orchard | |
| Access to grazing land | |
| Livestock | |
| Labour | |
| Agricultural equipment/tools | |
| Tractor and implements | |
| Draught power | |
| Other (specify) | |

**D2** If you have a homestead garden, what is the size of your land?

| | |
|---|---|
| >0.5 ha | |

| | |
|---|---|
| 0.5–1 ha | |
| 1–2 ha | |
| >2 ha | |

**D3** Did you plant any crops during the 2014/15 seasons?

| | |
|---|---|
| Yes | |
| No | |

**D4** If yes, what type of crops did you plant?

| | |
|---|---|
| Cabbage | |
| Potatoes | |
| Onions | |
| Beetroot | |
| Butternut/pumpkins | |
| Maize | |
| Tomatoes | |
| Other (specify) | |

**D5** What type of fertilizer(s) do you use when planting crops?

| | |
|---|---|
| Organic | |
| Inorganic | |

**D6** What type of irrigation system do you use in your gardening?

| | |
|---|---|
| Hand irrigation | |
| Sprinkler | |
| Drip | |
| Other (specify) | |

**E. FARMING SYSTEMS**

**E1** What is the average size of your homestead garden where crops are or can be produced?

**E2** What is the size of the area utilised in your homestead garden?

**E3** Why are you not utilising the whole area?

**E4** Are you utilising more or less of your homestead garden than in the past? Why?

**E5** Is the production increasing or decreasing? Why?

**E6** What production techniques are you practising? Why?

**E7** Do you collect water from the rooftop?

| | |
|---|---|
| Yes | |
| No | |

**E8** If 'yes' to E7, what are you using to capture it and what are you using it for?

**E9** Do you produce crops in winter?

| | |
|---|---|
| Yes | |
| No | |

**E10** If 'yes' to E9 , what type of crops are you producing in winter? List them with the most crops first to the least amount of crops last.

(i)
(ii)
(iii)
(iv)
(v)

**E11** Who works in the garden? When do they work (is there a time table)? How long do they work on a day?

**E12** What are the main inputs you have bought this season for your homestead garden and how much did it cost?

| Input type | Price of input | Units | Name of supplier | Distance from your place (km) | Transport method | Transportation cost |
|---|---|---|---|---|---|---|
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |

**E13** If you sold your output this season from your homestead garden, how much did you receive per output?

| Output type | Income per output | Units | How was the output? | Total income per output | Buyer (if possible) |
|---|---|---|---|---|---|
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

**E14** Do you know the soil texture in your homestead garden?

| | |
|---|---|
| Yes | |
| No | |

**E15** If you answered 'yes' in E14, specify.

| | |
|---|---|
| Sandy | |
| Loamy | |
| Clay | |

**E16** Do you have any weeds problem(s) in your homestead garden?

| | |
|---|---|
| Yes | |
| No | |

**E17** If 'yes' to E16, how do you control it?

**E18** Where do you get advice and support on weed control?

**E19** Do you produce for consumption, selling (marketing) purposes or for both

| | |
|---|---|
| Consumption | |
| Selling/marketing | |
| Both | |

**E20** What influenced you to plant the crops that you are planting? How do you decide on what to plant?

**E21** Do you have the necessary tools for backyard production?

| | |
|---|---|
| Yes | |
| No | |

**E22** Do you get any support from outside?

| | |
|---|---|
| Yes | |
| No | |

**E23** What problems are you faced with in terms of backyard (farming) production?

**E24** Do you think traditional beliefs restrict you from adopting new scientific techniques to develop your production? Please explain.

## F. CROPLAND PRODUCTION

**F1** Do you have access to croplands?

| | |
|---|---|
| Yes | |
| No | |

**F2** Do you own (PTO) it or is it a rented cropland?

| | |
|---|---|
| Own (PTO) | |
| Rented | |
| Other | |

**F3** How far are the croplands from the homesteads?

**F4** How did you acquire the cropland?

**F5** How long (years) have you been farming or producing on that land?

**F6** If you are not using your croplands, explain why.

**F7** What is the size of your cropland(s)?

**F8** How much (size or area) of that cropland is utilised?

**F9** If you do not utilise your cropland or the whole of it, explain why not.

**F10** What are the current conditions (used or not used) of the croplands?

**F11** Is the area well fenced?

| | |
|---|---|
| Yes | |
| No | |

**F12** Do you utilise your croplands every year?

| | |
|---|---|
| Yes | |
| No | |

**F13** If 'no' to F12, why?

**F14** What crops are you planting during summer in the croplands?

(i)
(ii)
(iii)
(iv)
(v)

**F15** Do you plant in winter?

| | |
|---|---|
| Yes | |
| No | |

**F16** If 'yes' to F15, what crops do you plant?

(i)
(ii)
(iii)
(iv)
(v)

**F17** What are the main inputs you have bought this season for your croplands and how much do they cost?

| Input type | Price of input | Units | Name of supplier | Distance from your place (km) | Transport method | Transportation cost |
|---|---|---|---|---|---|---|
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |

**F18** If you wanted to improve your income from cropland and had money, what will be your first and second priority?

| Priority | First priority | Second priority |
|---|---|---|
| Buy a tractor | | |
| Buy a vehicle like a lorry, truck or minibus | | |
| Buy or rent a new land for cultivation. | | |
| Buy inputs (e.g. fertilizers) | | |
| Invest in infrastructure (e.g. fences, boom spray, etc.) | | |
| Other (specify) | | |

**F19** If the village had money, what would the villagers like to invest in to increase cultivation income/product? What will be their second choice?

**F20** Do you have fixed planting dates?

| | |
|---|---|
| Yes | |
| No | |

**F21** If 'yes' to F20, please name or specify them.

**F22** If 'no' to F20, how do you determine when to plant?

**F23** Are you aware of the law that states that if you have not used your cropland for over 15 years you have to apply for a ploughing certificate?

| | |
|---|---|
| Yes | |
| No | |

**F24** If 'yes' to F23, how will this suppress or affect your production?

**F25** Do you have access to implements?

| | |
|---|---|
| Yes | |
| No | |

**F26** If 'yes' to F25, name them and how much they cost.

| Implement | Cost |
|---|---|
| | |
| | |
| | |

**F27** How accessible are the implements that you require to cultivate your croplands?

**F28** What production techniques and practices are you applying or using?

**F29** How much did you produce during the previous season of all your crops?

**F30** Do you receive any support and/or information?

| | |
|---|---|
| Yes | |
| No | |

**F31** If 'yes' to F30, state what type of support or information you receive and from whom?

**F31** In future, what type of support and/or information would you like to receive and from whom?

**F32** What type of labour do you use and how much do you pay them per day (if they are casual labourers)?

**F33** Are weeds a problem in you croplands?

| | |
|---|---|
| Yes | |
| No | |

**F34** If 'yes' to F33, how do you control it and when do you start with control?

**F35** How and when do you control insects and other related problems in your croplands?

**F36** Do you have access to markets for your crops?

| | |
|---|---|
| Yes | |
| No | |

**F37** If 'no' to F36, why not?

**F38** Are there any crops that you have sold this season from your croplands?

| | |
|---|---|
| Yes | |
| No | |

**F39** If 'no' to F38, state the reason.

| | |
|---|---|
| Reason | |
| Poor quality | |
| Lack of market access | |
| Did not produce this season | |
| Other (specify) | |

**F40** If 'yes' to F38, state which crops you sold and how much money you made from each crop?

| Type of crop | Income (R ) | How much (weight) | Total income per crop |
|---|---|---|---|
| Vegetables (specify) | | | |
| | | | |
| | | | |
| Maize | | | |
| Fruits (specify) | | | |
| | | | |
| | | | |

**F41** List any problems you experience on the croplands?

(i)
(ii)
(iii)
(iv)
(v)

**F42** What activities do you do during the season? Do you have a timetable for all seasonal activities such as weed control, soil preparation, pre-planting, planting, etc.?

**F43** Do you know the soil type of your cropland?

| | |
|---|---|
| Yes | |
| No | |

**F44** If ‘yes’ to F43, specify the soil type on your cropland.

| | |
|---|---|
| Sandy | |
| Loamy | |
| Clay | |
| I have no idea | |

**F45** Is the soil in the cropland shallow?

| | |
|---|---|
| Yes | |
| No | |
| Do not know | |

**F46** Does the soil in your cropland have a water logging problem?

| | |
|---|---|
| Yes | |
| No | |
| Do not know | |

**F47** Does the soil in your cropland erode easily?

| | |
|---|---|
| Yes | |
| No | |

**F48** If ‘yes’ to F47, what measures do you put in place to control soil erosion?

(i)
(ii)
(iii)

**F49** What additional information regarding your soils do you need in order to improve or maximise production on your croplands?.

**F50** Do you have any knowledge of RWH&C techniques?

| | |
|---|---|
| Yes | |
| No | |

**F51** Are you interested in learning more about RWH&C techniques?

| | |
|---|---|
| Yes | |
| No | |

**F52** Will you be interested in learning about new soil and water conservation and fertility management techniques?

| | |
|---|---|
| Yes | |
| No | |

**F53** If 'yes' to F52, tick which management practices are more suitable or interesting for you

| | |
|---|---|
| Management practices | |
| Chemical fertilizers | |
| Crop residues | |
| Organic farming | |
| Other (specify) | |

**F55** Are you currently doing anything to conserve water on your croplands?

| | |
|---|---|
| Yes | |
| No | |

**G. LIVESTOCK PRODUCTION AND ACCESS TO RANGELANDS**

**G1** Do you make use of rangelands?

| | |
|---|---|
| Yes | |
| No | |

**G2** How far are the rangelands from the homesteads?

**G3** Are they communal or government rangelands?

**G4** Who decides on the allowable number of livestock in the rangelands and where they should graze?

**G5** Do you have different grazing patterns?

| | |
|---|---|
| Yes | |
| No | |

**G6** How are the conditions of the rangelands?

**G7** How much livestock per household is allowed in the rangelands?

**G8** Are the any herders?

| | |
|---|---|
| Yes | |
| No | |

**G9** If somebody exceeds the number of livestock allowed in rangelands, is there a fine or punishment?

| | |
|---|---|
| Yes | |
| No | |

**G10** If 'yes' to G9, what type of fine or punishment is imposed on the individual?

**G11** What is the size of the rangelands that your village has access to?

**G12** Are the rangelands fenced?

| | |
|---|---|
| Yes | |
| No | |

**G13** What type of facilities are available in the rangelands?

(i)
(ii)
(iii)

**G14** Class the type and number of livestock you have.

| Animals | | Number of livestock |
|---|---|---|
| Cattle | Cows | |
| | Calves | |
| | Oxen | |
| Goats | Goats | |
| Pigs | Boar | |
| | Saw | |
| | Piglets | |
| Sheep | Rams | |
| | Ewes | |
| | Lambs | |
| Chickens | Hens | |
| | Cock | |
| Horses | | |
| Others (specify): | | |

**G15** What techniques and practices are you applying to improve the conditions of the rangelands?

**G16** Do you give supplementary or any additional feed to your livestock?

| | |
|---|---|
| Yes | |
| No | |

**G17** If 'yes' to G16 what, when and where do you get it?

**G18** Do you ever experience feed shortage for your livestock?

| | |
|---|---|
| Yes | |
| No | |

**G19** If 'yes' to G18, during which season or time of the year?

**G20** What do you think can be done to overcome this challenge?

**G21** Which livestock do you think are mostly affected by feed shortage?

**G22** Do you have access to markets for your livestock?

| | |
|---|---|
| Yes | |
| No | |

**G23** Do you have access to a veterinary surgeon?

| | |
|---|---|
| Yes | |
| No | |

**G24** If 'yes' in G23, how do you access the veterinary surgeon?

**G25** Do you vaccinate your livestock?

| | |
|---|---|
| Yes | |
| No | |

**G26** If 'no' to G25, mention why not.

**G27** Where and what type of vaccines and/or medication did you buy for your livestock this season?

| Supplier | Product | Unit price | How much purchased? |
|---|---|---|---|
| | | | |
| | | | |
| | | | |

**G28** Do you produce for consumption or selling (marketing) purposes or for both?

| | |
|---|---|
| Consumption | |
| Selling/marketing | |
| Both | |

**G29** Did you sell any of your livestock during this current period?

| | |
|---|---|
| Yes | |
| No | |

**G30** If you said 'no' to G29, state why not?

| Reason | |
|---|---|
| Poor quality | |
| Lack of market access | |
| Consumption purposes | |
| I do not want to sell now | |
| Other (specify) | |

**G31** If you said 'yes' to G29, please indicate how many and to whom did you sell to?

| Type of livestock sold | Price(R)/ livestock | Total number sold | Total income (R) | Whom did you sell to? |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |

**G32** What are the five main constraining factors that limit or suppress you from producing quality livestock?

(i)
(ii)
(iii)
(iv)
(v)

**G33** If the village had money, what would the villagers like to invest in to increase livestock production? What will be their second choice?

### H. ORGANISATIONAL ARRANGEMENTS AND FINANCIAL ACCESS

**H1** Did you receive any extension advice(s) from extension officer(s) this season?

| | |
|---|---|
| Yes | |
| No | |

**H2** Are you willing to pay for that extension service?

| | |
|---|---|
| Yes | |
| No | |

**H3** Which extension service do you prefer most?

| | |
|---|---|
| Government extension service(s) | |
| Cooperative extension service(s) | |
| Private extension service(s) | |
| None (I do not need them) | |
| Other (specify) | |

**H4** Have you ever received any assistance from the government or private extension officers this season ?

| | |
|---|---|
| Yes | |
| No | |

**H5** How many times have they visited you this season?

**H6** What kind of assistance did you receive?

| | |
|---|---|
| Farm management training | |
| Financial assistance | |
| Financial record keeping | |
| General advises | |
| Implements (e.g. tractors, plough, etc.) | |
| Livestock medicine | |
| Fertilizers | |
| Other (specify) | |

**H7** How will you rate or value the quality of extension officers?

| | |
|---|---|
| Good | |
| Fair | |
| Poor | |
| Never had assistance from the extension officer | |

**H8** Where do you get the information regarding quality production, pricing and market requirements?

| Source | Quality production | Pricing | Marketing requirements |
|---|---|---|---|
| Markets agents | | | |
| Radio | | | |
| Television | | | |
| Co-farmers | | | |
| Extension officer (NDoA) | | | |
| Extension officer (Co-op) | | | |
| Own pricing (decision) | | | |

| | | | |
|---|---|---|---|
| Inkosi (traditional leader) | | | |
| Newspapers (magazines) | | | |
| Input supplier(s) | | | |
| Farmers' union | | | |
| None | | | |
| Other (specify) | | | |

**H9** Which of the following organisations/services are easily available or accessible?

| | |
|---|---|
| Private or cooperative extension service | |
| Governmental extension service | |
| Input suppliers (e.g. Umtiza) | |
| Output markets | |
| Credit institutions | |
| Other (specify) | |
| None | |

**H10** Do you use any mechanisation (tractors, plough, implements, etc.) in the rangelands?

| | |
|---|---|
| Yes | |
| No | |

**H11** Do you have any access to transportation services?

| | |
|---|---|
| Yes | |
| No | |

**H12** What mode of transport do you use for either acquiring inputs or selling your produce?

| | |
|---|---|
| Rented | |
| Public | |
| Own | |
| Other (specify) | |

**H13** Did you get any financial access outside your farming business this season?

| | |
|---|---|
| Yes | |
| No | |

**H14** If 'yes' to H13, state the name of the source, type, interest rate, amount borrowed and outstanding?

| Source | Type (hire purchase/ bond/overdraft/ production loan) | Interest rate (%) | Amount borrowed (R) | Amount outstanding (R) |
|---|---|---|---|---|
| Commercial bank(s) | | | | |
| Agricultural Bank of South Africa (Land Bank) | | | | |
| Agricultural cooperative(s) | | | | |
| Other (specify) | | | | |
| Credit unions | | | | |
| Farmers' association(s) | | | | |
| Family and friend(s) | | | | |
| Stokvels | | | | |
| Other (specify) | | | | |

**H15** Do you (still) need financial credit?

| | |
|---|---|
| Yes | |
| No | |

**H16** Is financial credit available to your farming enterprise?

| | |
|---|---|
| Yes | |
| No | |

**H17** Have you ever been denied any financial assistance by financers?

| | |
|---|---|
| Yes | |
| No | |

**H18** If 'yes' or 'no' to H17, state the reason.

| | |
|---|---|
| The bank does not want to lend me money due to insufficient security (collateral) | |
| Do not need extra money (I have enough money of my own to buy inputs) | |
| The cost (interest) of money is too high | |
| I have no access to credit | |
| Do not know how to go about organising credit | |
| Poor repayment ability of farm | |
| Other (specify): | |

## I ACCESS TO WATER

**I1** Do you have access to water for both croplands and livestock?

| | |
|---|---|
| Yes | |
| No | |

**I2** From where do you access water?

| | |
|---|---|
| Taps | |
| Rivers | |
| Dams | |
| Boreholes | |
| Other | |

**I3** What do you think should be improved with regard to water for livestock and croplands in your area?

## J GENERAL ISSUES

**J1** What are your goals with regard to your agricultural production?

**J2** Do you have ambitions to go beyond what you are producing presently?

## K INSTITUTIONAL ARRANGEMENTS

**K1** Does the land (e.g. homestead, cropland) belongs to you officially?

| | |
|---|---|
| Yes | |
| No | |

**K2** Do you have a title deed for the land?

| | |
|---|---|
| Yes | |
| No | |

**K3** How did you receive it or who gave you the land (e.g. homestead, cropland)?

| | |
|---|---|
| Government | |
| King/Chief | |
| Induna | |
| Bought | |
| Inherited | |
| Leased | |
| Other (specify) | |

**K4** Are you a member of any farmers' union?

| | |
|---|---|
| Yes | |
| No | |

**K5** If 'yes' to K4, state the name of the union.

**K6** If 'no' to K4, why not?

**K7** How do you value the inputs of the farmers' union?

| | |
|---|---|
| Good | |
| Fair | |
| Poor | |

**K8** Are you aware of any traditional or governmental legislation relating to your farm and backyard production and/or marketing?

| | |
|---|---|
| Yes | |
| No | |

**K9** If 'yes' to K8, how do they affect your farming and homestead production and/or marketing?

| **Legislation** | **Effect / restriction** |
|---|---|
| | |
| | |
| | |
| | |

**K10** Are you familiar with the National Agricultural Marketing Act of 1996?

| | |
|---|---|
| Yes | |
| No | |

**K11** If 'yes' to K10, how does it affect you?

**K12** List the organisations within your village that contribute to agriculture.

(i)
(ii)
(iii)
(iv)

**K13** If there are organisations within your village, mention their roles or how are they contributing to uplift the community.

(i)
(ii)
(iii)
(iv)
(v)

**K14** Do these organisations work individually or together?

**K15** State any institutional arrangements that suppress production in rangelands and croplands or both and explain why you say that.

**K16** Are these institutional arrangements formal or informal? Explain.

**K17** Are these laws or institutional arrangements functional or dysfunctional? Explain

**K18** If it is functional, how is it suppressing/improving production in both rangelands and croplands?

(i)
(ii)
(iii)
(iv)

**K19** If it is dysfunctional, how is it suppressing/improving production in both rangelands and croplands?

(i)
(ii)
(iii)
(iv)

**K20** Are these institutional arrangements enforceable? If 'no', please explain.

(i)
(ii)
(iii)
(iv)

**K21** What were or are the consequences/penalty to someone who does not adhere to the law or institutional arrangements put in place? Who enforces those penalties?

(i)
(ii)
(iii)
(iv)

**K22** Which institutional arrangements would you like to see abolished? Which ones need to be brought back? Which do you suggest they should be introduced as an effort to improve production in both rangelands and croplands?

(i)
(ii)
(iii)
(iv)

**K23** Who do you think should be responsible for making sure that these laws or institutional arrangements are implemented and punish those who broke them? Why?

**K24** Are there any conflicts between crops and livestock producers in your village?

| | |
|---|---|
| Yes | |
| No | |

**K25** If ‘yes’ to K24, can you explain those conflicts?

**K26** Who preside over those cases?

**K27** The one who is found guilty, if they refuse to adhere to the judgment, what further steps are taking against them?

**L ENERGY-RELATED ISSUES**

**L1** What do use as energy source for cooking?

| | |
|---|---|
| Electricity | |
| Firewood | |
| Paraffin | |
| Cattle manure | |
| Other (specify) | |

**L2** What do use as energy source for lightning?

| | |
|---|---|
| Electricity | |
| Firewood | |
| Paraffin | |
| Cattle manure | |
| Other (specify) | |

**L3** Do you always use the same energy source for the same purpose?

| | |
|---|---|
| Yes | |
| No | |

**L4** If ‘no’ to L3, when do you use which energy source?

**L5** Is the different energy sources freely available?

| | |
|---|---|
| Yes | |
| No | |

**L6** If you need to buy energy, where do you buy it and what is the price of the different sources?

| Energy source | Supplier | Price |
|---|---|---|
| | | |
| | | |
| | | |

**L7** What do you think are the advantages and disadvantages of the different energy sources?

| Energy source | Advantage | Disadvantage |
|---|---|---|
| | | |
| | | |
| | | |
| | | |

**L8** Do you have access to electricity?

| | |
|---|---|
| Yes | |
| No | |

**L9** If you had access to biogas, will you make use of it?

| | |
|---|---|
| Yes | |
| No | |

**L10** For biogas production, sufficient manure is needed. Do you have access to manure at all times?

| | |
|---|---|
| Yes | |
| No | |

**THANK YOU**

**Appendix 2: Profile description of the Fort Cox/Valsrivier ecotope**

| | | | |
|---|---|---|---|
| | | **Soil Form** | Valsrivier |
| **Latitude and longitude** | 32°48´97´´ / 27°03´32´´ | **Soil family** | Luckhoff |
| **Land type no** | Fb881 | **Surface rockiness** | None |
| **Climate zone** | 3064S | **Surface stoniness** | None |
| **Altitude** | 409 m | **Occurrence of flooding** | None |
| **Terrain unit** | Valley bottom (5) | **Wind erosion** | None |
| **Slope** | 1% | **Water erosion** | None |
| **Slope shape** | Straight | **Vegetation / land use** | Agronomic cash crops |
| **Aspect** | East | **Water table** | 0 mm |
| **Micro relief** | None | **Weathering of underlying material** | Moderate physical and chemical |
| **Parent material solum** | Grey and red mudstone and sandstone | **Alteration of underlying material** | None |
| **Underlying material** | Shale | | |

| | | | |
|---|---|---|---|
| **Horizon** | **Depth (mm)** | **Description** | **Diagnostic horizons** |
| A | 0–300 | Dry; dry to dark greyish brown 10YR4/2, moist to very dark greyish brown 10YR3/2; disturbed; clay loam; moderate coarse, sub-angular blocky; very hard; few normal fine pores; fine cracks; few fine Mn, Fe mottels; many fine pedotubules; few roots; gradual smooth transition. | Orthic |
| B | 300–800 | Dry; dry to dark greyish brown 10YR4/2, moist to very dark greyish brown 10YR3/2; undisturbed; clay; strong sub-angular blocky; very hard; few normal fine pores; fine cracks; many clay cutans; many pedotubules; many fine bio-casts; many roots; gradual smooth transition. | Pedocutanic |
| C | 800–1,200 | Dry; dry to dark yellowish brown 10YR4/4, moist to dark yellowish brown 10YR3/4; undisturbed; clay; moderate medium sub-angular blocky; friable; few normal fine pores; few coarse distinct white lime mottles, slight effervescence; few clay cutans; many fine bio-casts; few roots. | Unconsolidated material without signs of wetness |

**Appendix 3: Physical and chemical analyses of the Fort Cox/Valsrivier ecotope**

| Horizon | Depth (mm) | Diagnostic horizon | Exchangeable cations ($mg\ kg^{-1}$) | | | | Phosphorus (Bray 1) ($mg\ kg^{-1}$) | Carbon (%) | Resistance (ohm) | pH ($H_2O$) | Particle size distribution (percentage) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | Sand | | | | Silt | | Clay |
| | | | Potassium | Calcium | Magnesium | Sodium | | | | | 2–0.5 mm | 0.5–0.25 mm | 0.25–0.106 mm | 0.106–0.05 mm | 0.05–0.02 mm | 0.02–0.002 mm | < 0.002 mm |
| A | 0–300 | Orthic | 28 | 684 | 2,440 | 417 | 130 | 1.63 | 710 | 7.98 | 7.8 | 7.1 | 24.4 | 16.7 | 17.8 | 10.0 | 13.8 |
| B | 300–800 | Pedocutanic | 64 | 1,423 | 1,086 | 362 | 71 | 0.65 | 830 | 8.83 | 0.2 | 1.9 | 25.9 | 20.0 | 19.4 | 12.1 | 18.7 |
| C | 800–1,200 | Unconsolidated material without signs of wetness | 163 | 1,607 | 2,520 | 2,894 | 49 | 0.44 | 850 | 9.14 | 0.2 | 2.1 | 25.7 | 19.1 | 20.6 | 12.3 | 17.7 |

**Appendix 4: Transpiration (Ev), evaporation from the soil surface (Es) and evapotranspiration (ET = Ev + Es), over three maize-growing seasons (2016/17 to 2019/20) for the various treatments on the Fort Cox/Valsrivier ecotope**

| **Parameter** | **Season** | **Soil management treatment and bio-slurry application (t ha$^{-1}$)** | | | | | | | | | | | | | | | | | | | | **Mean** | **LSD( p = 0.05)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Mulch** | | | | **Cover crop** | | | | **Manure** | | **Bare: Surface application** | | **Bare: Incorporate** | | **Bare: Water equivalent** | | **Bare: Spread application** | | | | | |
| | | 0 | 3 | 5 | 7 | 0 | 3 | 5 | 7 | 3 | 5 | 3 | 5 | 3 | 5 | 3 | 5 | 0 | 3 | 5 | 7 | | |
| Ev (mm) | 2016/ 2017 | 56 abc | 56 abc | 58 ab | 59 ab | 52 abcd | 53 abcd | 55 abc | 56 abc | 38 e | 39 de | 48 abcde | 51 abcde | 51 abcde | 52 abcde | 41 cde | 43 cde | 44 bcde | 45 abcde | 47 abcde | 48 abcde | **50** | 15 |
| | 2017/ 2018 | 73 ab | 73 ab | 73 ab | 74 a | 67 abc | 68 abc | 70 abc | 72 abc | 56 c | 57 bc | 64 abc | 66 abc | 66 abc | 67 abc | 59 abc | 61 abc | 60 abc | 60 abc | 61 abc | 62 abc | **65** | 16 |
| | 2019/ 2020 | 52 abc | 53 abc | 53 ab | 56 a | 48 abcdef | 49 abcde | 49 abcde | 51 abcd | 37 g | 38 fg | 46 bcdef | 47 abcdef | 47 abcdef | 48 abcdef | 40 efg | 41 efg | 42 defg | 43 defg | 44 cdefg | 45 bcdefg | **46** | 9 |
| | **Mean** | **60** | **60** | **61** | **63** | **56** | **56** | **58** | **59** | **44** | **45** | **53** | **54** | **55** | **55** | **47** | **48** | **49** | **50** | **51** | **52** | **54** | |
| Es (mm) | 2016/ 2017 | 130 bcd | 150 abcd | 148 abcd | 144 abcd | 142 abcd | 133 abcd | 138 abcd | 116 d | 149 abcd | 152 abcd | 164 ab | 141 abcd | 153 abcd | 174 a | 158 abc | 170 ab | 134 abcd | 142 abcd | 162 ab | 119 cd | **146** | 42 |
| | 2017/2018 | 141 abcd | 135 abcd | 121 d | 126 bcd | 125 cd | 117 d | 126 bcd | 129 bcd | 131 bcd | 133 bcd | 135 abcd | 139 abcd | 149 abc | 133 bcd | 134 bcd | 131 bcd | 145 abc | 150 ab | 159 a | 139 abcd | **135** | 25 |
| | 2019/ 2020 | 220 abc | 220 abc | 220 abc | 214 bc | 226 abc | 229[a] bc | 223 abc | 207 c | 233 ab | 234 ab | 225 abc | 226 abc | 232 ab | 232 ab | 232 ab | 229 abc | 240 a | 237 ab | 237 ab | 237 ab | **228** | 25 |
| | **Mean** | **164** | **168** | **163** | **161** | **165** | **159** | **162** | **151** | **171** | **173** | **175** | **169** | **178** | **180** | **175** | **177** | **173** | **176** | **186** | **165** | **169** | |
| ET (mm) | 2016/ 2017 | 186 bcde | 206 abcd | 212 abc | 194 abcde | 196 abcde | 186 bcd | 192 abcde | 171 de | 186 bcde | 191 abcde | 213 ab | 191 abcde | 209 abcd | 226 a | 192 abcde | 209 abc | 175 cde | 185 bcde | 200 abcde | 167 e | **196** | 37 |
| | 2017/ 2018 | 214 ab | 208 abcd | 194 cdef | 200 bcdef | 192 cdef | 184 f | 196 bcdef | 200 bcdef | 187 ef | 190 def | 199 bcdef | 204 abcde | 216 ab | 200 bcdef | 193 cdef | 191 cdef | 204 abcde | 211 abc | 220 a | 200 bcdef | **200** | 20 |
| | 2019/ 2020 | 272 a | 272 a | 274 a | 269 a | 274 a | 277 a | 271 a | 258 a | 270 a | 272 a | 271 a | 273 a | 280 a | 280 a | 272 a | 269 a | 282 a | 280 a | 281 a | 283 a | **274** | 25 |
| | **Mean** | **224** | **229** | **224** | **224** | **221** | **216** | **220** | **210** | **215** | **218** | **228** | **223** | **233** | **235** | **221** | **224** | **222** | **226** | **237** | **217** | **223** | |

| Parameter | Season | Soil management treatment and bio-slurry application (t $ha^{-1}$) | | | | | | | | | | | | | | | | | | | | Mean | LSD( p = 0.05) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mulch | | | | Cover crop | | | | Manure | | Bare: Surface application | | Bare: Incorporate | | Bare: Water equivalent | | Bare: Spread application | | | | | |
| | | 0 | 3 | 5 | 7 | 0 | 3 | 5 | 7 | 3 | 5 | 3 | 5 | 3 | 5 | 3 | 5 | 0 | 3 | 5 | 7 | | |
| Es/ET (%) | 2016/ 2017 | 68 b | 73 ab | 70 ab | 74 ab | 72 ab | 70 ab | 71 ab | 69 ab | 84 a | 78 ab | 76 ab | 74 ab | 71 ab | 76 ab | 82 ab | 81 ab | 77 ab | 76 ab | 81 ab | 71 ab | **75** | 15 |
| | 2017/ 2018 | 66 abc | 65 abc | 62 c | 63 bc | 65 abc | 63 bc | 64 abc | 64 abc | 70 abc | 70 abc | 68 abc | 68 abc | 69 abc | 67 abc | 69 abc | 69 abc | 71 ab | 71 ab | 72 a | 69 abc | **67** | 8 |
| | 2019/ 2020 | 81 efg | 81 efg | 80 fg | 79 g | 83 bcdef | 82 cdefg | 82 defg | 80 fg | 86 a | 86 ab | 83 abcdef | 83 abcdef | 83 abcdef | 83 abcdef | 85 abc | 85 abcd | 85 abcd | 85 abcd | 85 abcd | 85 abcde | **83** | 3 |
| | **Mean** | **72** | **73** | **72** | **71** | **74** | **72** | **73** | **71** | **79** | **78** | **76** | **75** | **76** | **76** | **78** | **78** | **77** | **77** | **78** | **75** | **75** | |

**Appendix 5: Biomass, grain yield and Harvest Index for the various treatments on the Fort Cox/Valsrivier ecotope over three maize-growing seasons (2016/2017 to 2019/2020)**

| Parameter | Season | Soil management treatment and bio-slurry application (t ha$^{-1}$) | | | | | | | | | | | | | | | | | | | | Mean | LSD (p = 0.05) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mulch | | | | Cover crop | | | | Manure | | Bare: Surface application | | Bare: Incorporate | | Bare: Water equivalent | | Bare: Spread application | | | | | |
| | | 0 | 3 | 5 | 7 | 0 | 3 | 5 | 7 | 3 | 5 | 3 | 5 | 3 | 5 | 3 | 5 | 0 | 3 | 5 | 7 | | |
| Biomass (kg ha$^{-1}$) | 2016/ 2017 | 4886 abc | 4891 abc | 5078 ab | 5219 a | 4603 abcde | 4647 abcd | 4789 abc | 4878 abc | 3305 e | 3435 de | 4234 abcde | 4441 abcde | 4482 abcde | 4525 abcde | 3612 cde | 3743 cde | 3876 bcde | 3962 abcde | 4136 abcde | 4222 abcde | 4348 | 1327 |
| | 2017/ 2018 | 6781 ab | 6793 ab | 6807 ab | 6939 a | 6269 abc | 6332 abc | 6529 abc | 6581 abc | 5234 c | 5365 bc | 5984 abc | 6133 abc | 6189 abc | 6212 abc | 5539 abc | 5588 abc | 5622 abc | 5705 abc | 5705 abc | 5741 abc | 6107 | 1460 |
| | 2019/ 2020 | 5473 abc | 5490 abc | 5611 ab | 5814 ab | 4967 abcdef | 5083 abcde | 5068 abcde | 5322 abcd | 3858 g | 4018 fg | 4843 bcdef | 4886 abcdef | 4956 abcdef | 5235 abcdef | 4137 efg | 4245 efg | 4503 defg | 4380 defg | 4548 cdefg | 4712 bcdefg | 4844 | 968 |
| | **Mean** | **5714** | **5725** | **5832** | **5991** | **5280** | **5349** | **5467** | **5627** | **4132** | **4273** | **5021** | **5154** | **5209** | **5235** | **4429** | **4525** | **4626** | **4718** | **4796** | **4892** | 5100 | |
| Grain yield (kg ha$^{-1}$) | 2016/ 2017 | 1377 abc | 1338 abcd | 1430 ab | 1450 ab | 1224 abcdef | 1253 abcdef | 1283 abcde | 1375 abc | 740 h | 880 gh | 1116 abcdefg | 1161 abcdefg | 1167 abcdefg | 1195 abcdefg | 918 fgh | 980 efgh | 981 efgh | 1029 defg | 1073 defgh | 1104 bcdefgh | 1154 | 336 |
| | 2017/ 2018 | 1557 abc | 1623 abc | 1712 ab | 1790 ab | 1473 abc | 1504 abc | 1539 abc | 1547 abc | 1226 c | 1268 bc | 1420 abc | 1426 abc | 1449 abc | 1468 abc | 1313 bc | 1324 bc | 1356 abc | 1390 abc | 1410 abc | 1399 abc | 1460 | 450 |
| | 2019/ 2020 | 1930 abc | 1940 abc | 1950 ab | 2251 a | 1845 abcde | 1904 abcd | 1914 abcd | 1928 abc | 1225 g | 1345 fg | 1758 bcdef | 1776 bcdef | 1723 bcdef | 1791 bcdef | 1432 efg | 1464 defg | 1488 cdefg | 1583 bcdefg | 1560 bcdefg | 1663 bcdefg | 1724 | 455 |
| | **Mean** | **1622** | **1634** | **1697** | **1831** | **1514** | **1554** | **1579** | **1617** | **1064** | **1165** | **1420** | **1448** | **1464** | **1485** | **1221** | **1256** | **1275** | **1326** | **1352** | **1393** | 1446 | |
| Harvest index | 2016/ 2017 | 0.28 a | 0.27 a | 0.28 a | 0.28 a | 0.28 a | 0.27 a | 0.27 a | 0.27 a | 0.23 a | 0.26 a | 0.26 a | 0.26 a | 0.26 a | 0.26 a | 0.25$^{a}$ | 0.25 a | 0.26 a | 0.26 a | 0.26 a | 0.26 a | 0.26 | 0.09 |
| | 2017/ 2018 | 0.24 a | 0.25 a | 0.23 a | 0.26 a | 0.23 a | 0.24 a | 0.23 a | 0.23 a | 0.24 a | 0.24 a | 0.23 a | 0.23 a | 0.24 a | 0.24 a | 0.24$^{a}$ | 0.24 a | 0.25 a | 0.24 a | 0.25 a | 0.24 a | 0.24 | 0.09 |
| | 2019/ 2020 | 0.39 a | 0.35 a | 0.35 a | 0.37 a | 0.38 a | 0.35 a | 0.38 a | 0.36 a | 0.33 a | 0.32 a | 0.36 a | 0.36 a | 0.36 a | 0.36 a | 0.35$^{a}$ | 0.34 a | 0.34 a | 0.35 a | 0.35 a | 0.35 a | 0.35 | 0.11 |
| | **Mean** | **0.29** | **0.29** | **0.29** | **0.31** | **0.29** | **0.29** | **0.29** | **0.29** | **0.26** | **0.28** | **0.29** | **0.28** | **0.28** | **0.29** | **0.28** | **0.28** | **0.28** | **0.28** | **0.28** | **0.29** | 0.29 | |

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

**Appendix 1: Precipitation use efficiency and rainwater productivity for the various treatments on the Fort Cox/Valsrivier ecotope over three maize-growing seasons (2016/2017 – 2019/2020)**

| Parameter | Season | IRWH treatment (t ha$^{-1}$) | | | | | | | | | | | | | | | | | | | | Mean | LSD (p = 0.05) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mulch | | | | Cover crop | | | | Manure | | Bare: Surface application | | Bare: Incorporate | | Bare: Water equivalent | | Bare: Spread application | | | | | |
| | | 0 | 3 | 5 | 7 | 0 | 3 | 5 | 7 | 3 | 5 | 3 | 5 | 3 | 5 | 3 | 5 | 0 | 3 | 5 | 7 | | |
| PUE$_{Gp}$ (kg ha$^{-1}$ mm$^{-1}$) | 2016/2017 | $9.0^{abcd}$ | $9.3^{abc}$ | $9.6^{abc}$ | $9.7^{a}$ | $8.2^{abcdef}$ | $8.6^{abcde}$ | $8.4^{abcdef}$ | $9.2^{abc}$ | $5.0^{h}$ | $5.9^{gh}$ | $7.5^{bcdefg}$ | $7.8^{abcdefg}$ | $7.8^{abcdefg}$ | $8.0^{abcdefg}$ | $6.2^{fgh}$ | $6.6^{efgh}$ | $6.6^{efgh}$ | $6.9^{defgh}$ | $7.2^{cdefgh}$ | $7.4^{bcdefg}$ | **7.8** | 2.3 |
| | 2017/2018 | $7.8^{abc}$ | $8.1^{abc}$ | $8.5^{ab}$ | $8.9^{ab}$ | $7.4^{abc}$ | $7.5^{abc}$ | $7.5^{abc}$ | $7.7^{abc}$ | $6.1^{c}$ | $6.3^{bc}$ | $7.1^{abc}$ | $7.1^{abc}$ | $7.2^{abc}$ | $7.3^{abc}$ | $6.6^{bc}$ | $6.6^{bc}$ | $6.8^{abc}$ | $6.9^{abc}$ | $7.0^{abc}$ | $7.0^{abc}$ | **7.3** | 2.2 |
| | 2019/2020 | $7.2^{abc}$ | $7.2^{ab}$ | $7.3^{abc}$ | $8.4^{a}$ | $6.9^{abcde}$ | $7.1^{abc}$ | $7.1^{abc}$ | $7.2^{abc}$ | $4.6^{g}$ | $5.0^{fg}$ | $6.4^{bcdefg}$ | $6.5^{bcdefg}$ | $6.6^{bcdef}$ | $6.7^{bcdef}$ | $5.3^{efg}$ | $5.4^{defg}$ | $5.5^{cdefg}$ | $5.8^{bcdefg}$ | $6.2^{bcdefg}$ | $5.9^{bcdefg}$ | **6.4** | 1.7 |
| | **Mean** | **8.1** | **8.1** | **8.5** | **9.0** | **7.5** | **7.7** | **7.8** | **8.0** | **5.2** | **5.8** | **7.0** | **7.2** | **7.2** | **7.3** | **6.0** | **6.2** | **6.3** | **6.6** | **6.7** | **6.9** | **7.2** | |
| RWP (kg ha$^{-1}$ mm$^{-1}$) | 2017/2018 | $3.3^{abc}$ | $3.5^{abc}$ | $3.7^{ab}$ | $3.8^{a}$ | $3.2^{abc}$ | $3.2^{abc}$ | $3.3^{abc}$ | $3.3^{abc}$ | $2.6^{c}$ | $2.7^{bc}$ | $3.0^{abc}$ | $3.1^{abc}$ | $3.1^{abc}$ | $3.1^{abc}$ | $2.8^{bc}$ | $2.8^{bc}$ | $2.9^{bc}$ | $3^{abc}$ | $3^{abc}$ | $3^{abc}$ | **3.1** | 2.2 |
| | 2019/2020 | $4.2^{abc}$ | $4.2^{ab}$ | $4.2^{ab}$ | $4.8^{a}$ | $4^{abcd}$ | $4.1^{abc}$ | $4.1^{abc}$ | $4.1^{abc}$ | $2.6^{f}$ | $2.9^{ef}$ | $3.7^{bcde}$ | $3.8^{bcde}$ | $3.8^{bcde}$ | $3.8^{bcde}$ | $3.1^{def}$ | $3.1^{def}$ | $3.2^{cdef}$ | $3.4^{bcdef}$ | $3.4^{bcdef}$ | $3.6^{bcdef}$ | **3.7** | 1.0 |
| | **Mean** | **3.7** | **3.8** | **3.9** | **4.3** | **3.6** | **3.7** | **3.7** | **3.7** | **2.6** | **2.8** | **3.4** | **3.4** | **3.5** | **3.5** | **2.9** | **3.0** | **3.1** | **3.2** | **3.2** | **3.3** | **3.4** | |

Different superscripts within a row indicate a significant difference (P ≤ 0.05); values with similar superscripts are not significantly different (P ≤ 0.05).

**Appendix 7: Species composition at various sites**

| Locality | Plant species | Ecological status | Grazing value | Plant form | Mean abundancy (%) |
|---|---|---|---|---|---|
| Krwakrwa –illage | *Digitaria eriantha* | Decreaser | High | Perennial | 7.7 |
| | *Eragrostis capensis* | Increaser II | Moderate | Perennial | 16.3 |
| | *Sporobolus fimbbriatus* | Decreaser | High | Perennial | 1.0 |
| | *Cymbopogon pospischilii* | Increaser III | Low | Perennial | 0.3 |
| | *Sporobolus africanus* | Increaser III | Low | Perennial | 10.3 |
| | *Eragrostis chloromelus* | Increaser II | Moderate | Perennial | 0.3 |
| | *Eragrostis curvula* | Increaser II | Moderate | Perennial | 9.3 |
| | *Hyparrhenia hirta* | Increaser I | Moderate | Perennial | 10.0 |
| | *Cynodon dactylon* | Increaser II | High | Creeping perennial | 18.3 |
| | *Aristida congesta* | Increaser II | Low | Weak perennial | 21.7 |
| | *Eragrostis obtusa* | Increaser II | Moderate | Weak perennial | 1.0 |
| | *Eragrostis plana* | Increaser II | Low | Perennial | 3.7 |
| Shared grazing near the Chief's homestead | *Digitaria eriantha* | Decreaser | High | Perennial | 0.5 |
| | *Eragrostis capensis* | Increaser II | Moderate | Perennial | 24.5 |
| | *Themeda triandra* | Decreaser | High | Perennial | 26.5 |
| | *Heteropogon contortus* | Increaser II | Moderate | Perennial | 1.0 |
| | *Sporobolus africanus* | Increaser III | Low | Perennial | 11.0 |
| | *Eragrostis chloromelus* | Increaser II | Moderate | Perennial | 1.0 |

| Locality | Plant species | Ecological status | Grazing value | Plant form | Mean abundancy (%) |
|---|---|---|---|---|---|
| | *Eragrostis curvula* | Increaser II | Moderate | Perennial | 4.0 |
| | *Hyparrhenia hirta* | Increaser I | Moderate | Perennial | 12.5 |
| | *Cynodon dactylon* | Increaser II | High | Perennial | 5.0 |
| | *Microcloa caffra* | Increaser II | Low | Perennial | 3.5 |
| | *Aristida congesta* | Increaser II | Low | Weak perennial | 0.5 |
| | *Eragrostis plana* | Increaser II | Low | Perennial | 9.5 |
| | *Forbs* | Increaser II | Low | Unknown | 0.5 |
| Shared grazing near thorntrees | *Brachiaria serrata* | Decreaser | Moderate | Perennial | 0.7 |
| | *Digitaria eriantha* | Decreaser | High | Perennial | 15.7 |
| | *Eragrostis capensis* | Increaser II | Moderate | Perennial | 10.7 |
| | *Themeda triandra* | Decreaser | High | Perennial | 15.3 |
| | *Sporobolus fimbbriatus* | Decreaser | High | Perennial | 1.0 |
| | *Cymbopogon pospischilii* | Increaser III | Low | Perennial | 1.3 |
| | *Sporobolus africanus* | Increaser III | Low | Perennial | 2.7 |
| | *Eragrostis chloromelus* | Increaser II | Moderate | Perennial | 2.3 |
| | *Eragrostis curvula* | Increaser II | Moderate | Perennial | 8.3 |
| | *Hyparrhenia hirta* | Increaser I | Moderate | Perennial | 4.0 |
| | *Eragrostis racemosa* | Increaser II | Moderate | Perennial | 0.3 |
| | *Cynodon dactylon* | Increaser II | High | Creeping perennial | 11.0 |

| Locality | Plant species | Ecological status | Grazing value | Plant form | Mean abundancy (%) |
|---|---|---|---|---|---|
| | *Microcloa caffra* | Increaser II | Low | Perennial | 3.3 |
| | *Aristida congesta* | Increaser II | Low | Weak perennial | 9.7 |
| | *Eragrostis obtusa* | Increaser II | Moderate | Weak perennial | 2.7 |
| | *Eragrostis plana* | Increaser II | Low | Perennial | 10.3 |
| | *Forbs* | Increaser III | Low | Unknown | 0.7 |
| Shared grazing near reservoir | *Digitaria eriantha* | Decreaser | High | Perennial | 0.5 |
| | *Eragrostis capensis* | Increaser II | Moderate | Perennial | 22.2 |
| | *Themeda triandra* | Decreaser | High | Perennial | 31.3 |
| | *Heteropogon contortus* | Increaser II | Moderate | Perennial | 0.5 |
| | *Sporobolus africanus* | Increaser III | Low | Perennial | 8.1 |
| | *Eragrostis chloromelus* | Increaser II | Moderate | Perennial | 1.0 |
| | *Eragrostis curvula* | Increaser II | Moderate | Perennial | 5.6 |
| | *Hyparrhenia hirta* | Increaser I | Moderate | Perennial | 4.0 |
| | *Cynodon dactylon* | Increaser II | High | Creeping perennial | 6.6 |
| | *Microcloa caffra* | Increaser II | Low | Perennial | 7.1 |
| | *Aristida congesta* | Increaser II | Low | Weak perennial | 1.5 |
| | *Eragrostis plana* | Increaser II | Low | Perennial | 10.1 |
| | *Forbs* | Increaser III | Low | Unknown | 1.5 |

| | | | | | |
|---|---|---|---|---|---|
| Upper Ncera rangelands | *Brachiaria serrata* | Decreaser | Moderate | Perennial | 1.0 |
| | *Eragrostis capensis* | Increaser II | Moderate | Perennial | 17.5 |
| | *Themeda triandra* | Decreaser | High | Perennial | 22.5 |
| | *Elionurus muticus* | Increaser III | Low | Perennial | 4.0 |
| | *Heteropogon contortus* | Increaser II | Moderate | Perennial | 7.0 |
| | *Sporobolus africanus* | Increaser III | Low | Perennial | 16.0 |
| | *Eragrostis chloromelus* | Increaser II | Moderate | Perennial | 1.0 |
| | *Eragrostis curvula* | Increaser II | Moderate | Perennial | 5.0 |
| | *Hyparrhenia hirta* | Increaser I | Moderate | Perennial | 5.5 |
| | *Cynodon dactylon* | Increaser II | High | Perennial | 2.0 |
| | *Microcloa caffra* | Increaser II | Low | Perennial | 0.5 |
| | *Eragrostis plana* | Increaser II | Low | Perennial | 16.0 |
| | *Forbs* | | Low | Unknown | 2.0 |

**Appendix 8: Questionnaire that is used to determine the social acceptability and technical information required to decide about the financial and economic benefits to a household**

## Up-scaling of rainwater harvesting and conservation to croplands and rangelands for food and renewable fuel (biogas) production

WRC Project K5/2495//4

University of Fort Hare
Together in Excellence

**Section 1: IDENTIFICATION**

| | |
|---|---|
| Beneficiary Name | |
| ID Number | |
| Telephone/Mobile | |
| Street Address | |
| Village/Town | |
| Unique Identifier | K5/2495//4/dd - mm - yyyy/# |

Please request to take an ID photo

**Section 2: SITE DETAILS**

| Number of | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Bedrooms | | | | | | | | |
| Persons Living Here | | | | | | | | |
| Lights on Premises (W) | | | | | | | | |
| Description of TV (W?) | | | | | | | | |

| Source of Cooking? | Wood = 1 | Paraffin = 2 | Electricity = 3 | |
|---|---|---|---|---|
| Microwave (W) | | | | |
| Kettle (W) | | | | |
| Stove with Oven | | | | |
| 2-plate Stove (W) | | | | |

| Main Source of Water? | Tank (5000L) = 1 | Municipal Tap = 2 | Communal Tap = 3 |
|---|---|---|---|
| Water Usage | Tank | Municipal | Communal |
| Drinking | | | |
| Washing Dishes | | | |
| Washing Clothes | | | |
| Irrigation | | | |
| Supplemental Irrigation | | | |

| Boolean | Yes=1/No=0 |
|---|---|
| Building Structure: Bricks | |
| Building Structure: Blocks | |
| Other (Describe) | |

| Boolean | Yes=1/No=0 |
|---|---|
| Roof: Corrugated Iron | |
| Roof: Thatch | |
| Other (Describe) | |

**Section 3: ELECTRICITY USAGE**

| ± Daily time of use (hours) | ½ | ¾ | 1½ | 1¾ | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|---|
| Lights | | | | | | | | |
| Microwave | | | | | | | | |
| Kettle | | | | | | | | |
| Stove with Oven | | | | | | | | |
| 2-plate Stove | | | | | | | | |

| | |
|---|---|
| Do you have a pre-paid meter? (Yes=1/No=0) | |
| Please request permission to record the pre-paid meter number | |
| Are you receiving 50 units Free Basic Electricity? (Yes=1/No=0) | |
| Approximately how much (additional) money do you spend on electricity/month? | |

**Section 4: BIOGAS DIGESTERS**

| | |
|---|---|
| Do you know how Biodigesters turn waste into gas for cooking? (Yes=1/No=0) | |
| Would you be willing to use manure to generate gas for cooking? (Yes=1/No=0) | |

**Appendix 9: Economic evaluation**

A sound economic evaluation of any project is a fundamental requirement that takes place during the pre-feasibility and feasibility analysis of a project when it requires assistance from the bank or financial commitment. The economic evaluation of the project is based on the following economic indicators: total investment cost, total income, energy cost, the cost of maintenance, profitability, payback period, net profit value, internal rate of return, annuity and cost annuity. These are determined to evaluate and assess the desirability and feasibility of the biogas digester project. The economic indicator or parameter is determined using a guide for the financial evaluation of investment projects in energy supply by Finck and Oelert (1985).

**Net present value**

Net present value is the sum of the present value of all the cash inflow and outflow that is linked to the investment of the biogas digester project at time *t = 0*. The formula for calculating NPV is:

$$NPV = -I_0 + \sum_{t=0}^{r}(R_t - I_t)q^{-t} + L_T q^{-T} \tag{1}$$

Equation 1 can also be written as:

$$NPV = -I_0 + (R \times PF) + L_T q^{-T} \tag{2}$$

Where, $I_0$ = Investment cost (R) at the beginning of the project, T is the lifetime of the project in years, R or $R_t$ is the annual returns/return in time period t, $I_t$ is the investment in time period t, PF is the present value factor (years), $L_T$ is the liquidation yield or salvage value and the $q^{-t}$ is the discount factor calculated as:

$$q^{-t} = \left(1 + \frac{i}{100}\right)^{-t} \tag{3}$$

**Internal rate of return**

Internal rate of return is the achievable interest tied up in an investment of a project. It computes at what interest the NPV will be zero.

$$0 = -I_0 + \sum_{t=0}^{T} R_t \left(1 + \frac{IRR}{100}\right) + L_T \left(1 + \frac{IRR}{100}\right)^{-T} \tag{4}$$

The internal rate of return can thus be expressed as:

$$IRR = I_i - NPV\left(\frac{i_2 - i_1}{NPV_2 - NPV_1}\right) \tag{5}$$

**Profitability or return on investment**

Profitability of return on investment (ROI) measures the performance of a project average profit per time interval. This is done by dividing the net profit by the net worth. A high return on investment favours the cost of the investment. The return on investment is a parameter used to relate profit and capital used in an investment. However, the profitability of return on investment is expressed as:

$$ROI = \frac{net\ profit}{total\ investment} \times 100 \tag{6}$$

**Annuity**

Annuity is the fixed sum of money paid annually for an investment or project. There are fixed and variable annuities. The annuity is calculated as:

$$A = NPV \times RF(i, T) \tag{7}$$

Where RF is the capital recovery factor, calculated as follows, and i and T are the discount rate and period in years respectively:

$$RF = \frac{q'(q-1)}{q'-1} \tag{8}$$

**Cost annuity**

The cost annuity, denoted as $A_k$, is the annual cost of the biogas project (Mukumba et al., 2013). Its usefulness is in evaluating the favourability of the investment project based on cost per annum (Finck and Olert, 1985). Cost annuity is calculated as:

$$A_k = K_0 + (I_0 - L) \times RF(i, t) + L \times I \tag{9}$$

Where $K_0$ is the operating cost per unit time, $I_0$ is the investment cost, L is the liquidation time (years), $R_F$ is the recovery periods (years), while i and t are the interest rate (%) based on assumption and project duration respectively.

**Operating and maintenance**

Cost of maintenance is calculated as 2% of the total investment cost divided by the lifetime of the biogas digester, that is:

$$O\&M = \frac{2\%\ of\ total\ cost\ of\ Investment}{Number\ of\ years\ of\ the\ system} \tag{10}$$

The operating and maintenance cost is the expenditures on labour on an annual basis. For instance, one unskilled labourer responsible for the feeding and cleaning of the biogas digester and a skilled labourer to manage it, as well as performing advanced tasks regarding the biogas digester. In addition, the cost of replacing the gas valve and pipe is included in the cost of maintenance.

## Appendix 10: Knowledge dissemination and capacity building

"Dissemination is the interactive process of communicating knowledge to target audiences so that it may be used to lead to change". Knowledge dissemination is a fundamental part of knowledge management for the reason that it ensures that knowledge is available and shared with those who need it. Sankarasubramanian (2009) stated that "knowledge" is the one thing that is common to all projects, as it is the most important resource needed for project management. It further goes with educating and training.

The knowledge dissemination activities to build the capacity of the villagers, scholars and students are aimed at empowering them with the necessary knowledge and skills to improve production in the homestead gardens, croplands and rangelands, and to use biogas as a renewable energy source. The whole process was followed by sharing knowledge on various platforms, such as formal and informal training events, farmers' days and information days. The new knowledge was also shared with the broader public at scientific workshops, conferences, congresses and publications in popular magazines and scientific journals.

### Capacity building and knowledge dissemination to villagers

The project started at Krwakrwa Village, so the idea was to use it as a good example for the implementation of the RWH&C technologies. It could then be used as a reference for neighbouring villages for the adoption of these new technologies. This was achieved through the hard work and dedication by the project team and villagers. Households were selected for the implementation of roof water harvesting and biogas production systems, followed by continuous training. Villagers received formal and practical or hands-on training on the implementation and maintenance of the technologies, as well as all aspects of production in the homestead gardens, croplands and rangelands.

#### *Food production in homestead gardens*

Villagers were taught that the IRWH crop production system works well on clayey soils. However, very few villagers knew the soil type at their homestead gardens, nor did they have an idea of the effective soil depths in their gardens. Villagers firstly received training on how to identify the soils. This was followed by training on the construction and maintenance of IRWH structures. Later, training was given on the planting of various vegetable crops within the IRWH system. In all these cases, researchers and technical assistants from the project team explained the theory, which was followed by practical demonstrations. For example, where IRWH basins were constructed, the technical assistants constructed one or two rows of basins, which the villagers observed and learnt how it was done. Villagers then had to continue with the construction of the basins in the rest of the homestead garden under the watchful eye of the technical assistants. Training was done in groups, but technical assistants regularly visited the individual homestead gardens for the duration of the project and provided one-on-one training where needed.



***Biogas production and usage***

The villagers were not at all familiar with the use of biogas as a renewable energy source. They gained knowledge on how a digester functioned and how to use the gas for cooking and bio-slurry as fertilizer. The villagers therefore had to receive formal training on the principles of biogas production and how to use the bio-digesters. They furthermore received hands-on training on the feeding, unblocking and maintenance of the digesters. The villagers also received training on when and how to apply the bio-slurry as a fertilizer. Most of the villagers were elderly and found it difficult to grasp the concept of biogas production, so the training had to be repeated several times.

**Capacity building and knowledge dissemination to students**

Researchers from the project team embarked on regular field trips to the Eastern Cape to provide training to the Fort Cox College students on various topics (including IRWH, biogas, seedlings production, value adding, marketing and communication). Training was given to the second-year students studying crop sciences and agri-business. Training was conducted for a period of three years, since the project was using the Fort Cox College's croplands for the on-station experimental plot. More than 300 students attended the training over the duration of the project.

Students not only received theoretical training, but also practical training. The practical training was conducted at the cropland experimental plots. Training included the installation of the neutron water meter access tubes, measuring soil moisture content and chemical weed control. At flowering and harvest, student assisted in taking biomass samples and recording maize grain yield.

**Capacity building and knowledge dissemination to scholars**

Various meetings were held with the principals of the schools in the two villages with the aim of involving the leaners in project activities and to exposing them to the new technologies. It was decided to have a competition between the schools and between grades within a school to get the scholars actively involved.

High school learners focused on water management, gardening and biogas production, while primary school learners only competed in the categories on water management and gardening. The training of the primary school scholars included biogas production, despite them not being involved in the biogas production, but only in the crops and water management. The purpose was to make them aware of the technology, since some of their parents were beneficiaries who had received bio-digesters.

The project provided all the necessary materials and inputs, such as measuring tapes and seedlings. Teachers consulted with tractor owners, some of whom were parents of the leaners at the schools, to assist with the ploughing of the school gardens before the IRWH basins were constructed. On the day of implementation and planting, scholars were requested to come with their own spades and rakes from home to assist with the activities in the school garden. Scholars received hands-on training on the construction of IRWH basins and planting of various vegetable crops. The idea was that scholars could apply what they had learned in the school gardens at home. The scholars could then help their parents in their homestead gardens as many of their parents were already using IRWH for food production. Further training was done with scholars on a continuous basis, including the capturing of crop production records, rainfall measurement and measurement of the roof water in the tanks harvested during rainy days and its usage. Scholars had to present the results at a mini-school conference to receive a cash prize for the school, which enabled them to buy more seedlings to be planted in the school garden. All the crops produced at these school gardens were given to the school feeding schemes.

**Capacity building of project team members**

Capacity building or training was not only meant for villagers, students and scholars, but team members coming from different backgrounds also had to familiarise themselves with the new technologies. Training among the project team members included soil classification, the installation of Neutron water meter access tubes, monitoring the soil water content with a Neutron water meter and DFM probe, species composition assessment in the rangelands, and the feeding and repair of the bio-digesters. Adding professional development opportunities while working on the projects provided project team members with a variety of benefits, including opportunities to immediately apply new skills and knowledge, personal and professional growth and a continuous learning environment.

**Workshops**

Various workshops were held with the aim of further empowering villagers and relevant stakeholders on the use and application of the new technologies. Furthermore, they enabled training on the different aspects of agricultural production and agribusiness. Topics and training included the maintenance of the bio-digesters, use of biogas, role and importance of committees, leadership, communication, record keeping, value adding and weed control.

**Farmers' days and information days**

A number of the farmers' days were held to display the hard work of the selected beneficiaries to the stakeholders and other villagers within the village who were not participating in the project. During the farmers' days and information days, the technologies got more exposure and experts from science and agriculture gave advice on different aspects. That included giving advice on avoiding the circumstances that could lower crop production or even result in spoiling their agricultural produce. Attending these farmers' days and information days was highly beneficial for the villagers for the development of their farming enterprises.

The farmers' days and information days were held each year around flowering time. Three homestead gardens and the cropland experimental plot at Fort Cox College were visited. Each year, three different homesteads gardens were chosen to give other beneficiaries a chance to showcase their gardens and share their knowledge and challenges with the attendees. Rangelands were also visited, where project team members shared information on the legumes that were planted within the enclosure cages aimed at improving the carrying capacity of the rangelands. The farmers' days and information days were concluded with a workshop where everyone reflected on what they had experienced during the day. The project team then answered questions raised by attendees during the discussions.



**Conferences and congresses**

Research findings were shared with experts within their field of expertise at various conferences and congresses. Project team members presented a number of scientific oral and poster presentations.

ANDERSON JJ and BOTHA JJ (2017). Suitability of Krwakrwa village for in-field rainwater harvesting. In: Combined Congress, Bela-Bela, South Africa, January 2017. [Prize awarded by the SSSSA for the Best Poster presentation]

BOTHA JJ and ANDERSON JJ (2016). In-field rainwater harvesting: Key to smallholder productivity. In: Combined Congress, University of the Free State, Bloemfontein, South Africa, 18–21 January 2016. [Silver medal from the SSSSA for the Best Poster presentations]

BOTHA JJ and ANDERSON JJ (2017). Rainwater harvesting through in-field runoff. In: Combined Congress, Bela-Bela, South Africa, January 2017.

BOTHA JJ and ANDERSON JJ (2018). Evaluating various large-scale rainwater harvesting and conservation techniques on the Fort Cox/Valsrivier ecotope. In: African Combined Conference, Cape Town, South Africa, 14–18 January 2018. [Prize awarded by the SSSSA for the Best poster presentation]

BOTHA JJ, ANDERSON JJ and KOATLA TAB (2016). Rainwater harvesting: Climate smart sustainable techniques for homestead and cropland production. In: Seminar session on Water, Agriculture and Food Security under the Impact of Climate Change, ARC-SCW, Pretoria, South Africa, 2 September 2016.

BOTHA JJ, ANDERSON JJ and KOATLA TAB (2017). Rainwater harvesting: Climate-smart techniques for increased smallholder productivity. In: Joint conference of the African Forum for Agricultural Advisory Services (AFAAS), South African Society for Agricultural Extension (SASAE) and Department of Agriculture, Forestry and Fisheries (DAFF), Durban, South Africa, 29 October–3 November 2017.

BOTHA JJ, ANDERSON JJ and KOATLA, TAB (2017). Up scaling rainwater harvesting techniques in homesteads and croplands for sustainable food production in rural areas. In: 4th Global Science Conference on Climate-Smart Agriculture, Johannesburg, South Africa, 28–30 November 2017.

BOTHA JJ, ANDERSON JJ, MDIBE N, NHLABATSI NN and KOATLA TAB (2018). Effectiveness of communication channels on the adoption of the in-field rainwater harvesting technique. In: LandCare Conference, Bloemfontein, South Africa, 25–27 September 2018.

GULWA U and THUBELA T (2018). Determining rainwater use efficiency, dry matter production and soil nutrient replenishing potential of dryland pastures produced in the old arable lands of Krwakrwa communal area, Eastern Cape, South Africa. In: Grassland Society of Southern Africa (GSSA) Conference.

KECHRIST O and MEYER E (2018). Design and fabrication of a biogas digester system. In: University of Fort Hare Renewable Energy (UFHRE) Symposium.

KECHRIST O and MEYER E (2018). Design and performance monitoring of a fabricated biogas digester using plastics. In: South Africa Institute of Physics (SAIP) Conference.

KOATLA TAB & BOTHA JJ (2016). The role of traditional leaders in the adoption of rainwater harvesting techniques and institutional arrangements: Case study of Krwakrwa, Eastern Cape Province. In: 7th Biennial National LandCare Conference, Kimberley, South Africa, 2–6 October 2016.

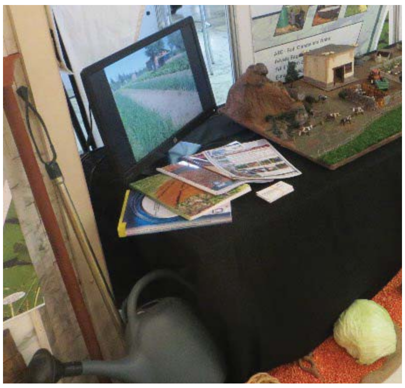
KOATLA TAB, BOTHA JJ and ANDERSON JJ (2017). Rainwater harvesting and conservation techniques: Analysis of institutional arrangements in Krwakrwa village, Eastern Cape. In: Joint DAFF, AFAAS and SASAE Conference at the AFAAS Africa Extension Week, Durban, South Africa, 29 October–3 November 2017.

NGQELENI VD, BOTHA JJ and CHIDUZA C (2017). Literature review: Evaluating suitability, effectiveness and application of bio-slurry as an organic fertilizer in communal areas of the Eastern Cape, South Africa. In: Combined Congress, Bela-Bela, South Africa, January 2017.



**Exhibitions and demonstrations**

Various exhibitions were held at conferences, congresses, workshops and farmers' days across the country. Project team members showcased work on RWH&C and biogas production. A three-dimensional scale model of a typical water harvesting and biogas production in a rural setting was built and displayed to help visitors to the exhibition understand the system.




**Radio talks**

The project got exposure through various media levels and public spaces. One such exposure tool was via radio interviews broadcast on various radio stations.

ANDERSON JJ (2019). *Application of rainwater harvesting* (Afrikaans). NAMPO Harvest day Radio. 16 May 2019.

BOTHA JJ (2016). *Application of rainwater harvesting and biogas production for food security and energy supply* (Afrikaans). RSG Landbou Radio. 26 August 2016 at 04:45.

BOTHA JJ (2016). *Principles of rainwater harvesting* (Afrikaans). RSG Landbou Radio. 19 October 2016 at 04:30.

BOTHA JJ (2016). *Rainwater harvesting and biogas production for household food security* (Afrikaans). RSG Landbou Radio. 2 November 2016 at 04:30.

BOTHA JJ (2016). *Commercial application of rainwater harvesting techniques* (Afrikaans). RSG Landbou Radio. 19 August 2016 at 04:45.

BOTHA JJ (2017). *Application of rainwater harvesting techniques to improve household food security* (Afrikaans). Groot FM Radio. Lynnwood, Pretoria.

BOTHA JJ (2019). *Basic principles of rainwater harvesting and its application to improve household food security* (Afrikaans). RSG Landbou Radio. 8 August 2019.

**Televisions interviews**

Television interviews were conducted with the project leader where information was shared with viewers regarding the RWH&C techniques.

BOTHA JJ (2016). *Use of rainwater harvesting for crop production*. Recorded at Hlasela Tlala ka Diratswana Festival, Glen. Broadcasted on SABC2 (Afrikaans) and SABC3 (English) news on the 30 January 2016.

BOTHA JJ (2016). *Use of rainwater harvesting for crop production*. Recorded at Grootplaas studio, Lynwood, Pretoria. Broadcasted on Grootplaas (KykNET Channel 144) on the 23 September 2016 at 05:30.

**Popular articles**

The project team managed to publish three popular articles.

BOTHA JJ & ANDERSON JJ (2016). *Rainwater harvesting and biogas production to enhance household food security and energy production*. FarmBiz. October 2016.

BOTHA JJ & ANDERSON JJ (2016). *Using rainwater and biogas for food security and energy*. Stockfarm. November 2016.

KOATLA TAB (2020). *Climate-smart agricultural technologies adopted by rural communities in Eastern Cape*. NuFarmer Africa. 24 (4).

**Manuscripts: Postgraduate students**

A number of students were identified to conduct their MSc and PhD studies on the project. Unfortunately, most of them have not completed their studies due to job opportunities or poor performance. Those who have completed their studies successfully and graduated are listed below.

KECHRIST O (2019). Modelling, design and performance monitoring of a biogas digester fabricated using plastic for deployment both underground and aboveground. PhD. University of Fort Hare.

KHAMKHAM T (2020). Evaluation of in-field rainwater harvesting technique, mulching and bio-slurry on dryland maize production on the Fort Cox/Valsrivier ecotope. MSc. University of Fort Hare.