Determining Water Use and Impacts on Water Resources of Cannabis in the Eastern Cape and KwaZulu–Natal Provinces

Report to the

Water Research Commission

by

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Executive Summary

Introduction and project aim

Interest in *Cannabis sativa* is growing globally and in South Africa, and the reasons for this are varied as it is a multipurpose crop that can be grown for fibre, seed, oil and medicinal properties. Hemp and marijuana both come from the same species *C. sativa*, with the difference being that hemp has a tetrahydrocannabinol (THC) content of less than 0.3% and is typically cultivated for fibre or seeds, whilst a THC percentage higher than 0.3% classifies the plant as marijuana.

Despite the potential benefits, economic and environmental, the water use of *C. sativa* remains largely unknown beyond the understanding that it is a water thirsty plant. The water use, or total evaporation of *C. sativa* has not been measured for growing conditions in South Africa, and estimates in the international literature are nearly non-existent.

Given the growing interest in and promotion of *C. sativa* cultivation in South Africa, the need to determine the water use of this crop and the associated impacts on hydrological response has become critical. Understanding the water use and related impacts will allow for informed decisions regarding *C. sativa* cultivation to be taken and will prevent adverse impacts on already stressed water resources.

With this background, the aims of the project were five-fold:

1. To conduct a scoping review of available literature on the water use, distribution and agronomic management and value chain of *C. sativa* crops for both fibre and oil production.
2. To map the extent and distribution of *C. sativa* stands as well as identify suitable growth areas.
3. Determine the water use and yield of *C. sativa* for either fibre or oil production using field- based measurements.
4. Undertake multi-scale modelling of the water use, yield and potential hydrological impacts of *C. sativa*.
5. Undertake a preliminary socio-economic feasibility assessment based on value chain principals including suitable areas for growth and best management practices.

The following summarises the research that was conducted under the project.

Aim 1 summary of research findings

A systematic literature review revealed no studies specifically addressing water use efficiency (WUE) in South Africa. The bibliometric data were further analysed using R statistical software. The analysis revealed a growing number of scientific publications and citations from 2010 to 2021. Most outputs were in medical journals, with the *South African Journal of Psychiatry* hosting the highest number of articles. Environmental research appeared less prominently, with the *International Journal of Environmental Research* ranking seventh in publication volume.

The lack of research on WUE in South Africa underscored a critical gap in the literature. This gap emphasizes the need for future studies to explore the interplay between water use and cannabis production, particularly given the increasing interest in cannabis-related research and its implications for sustainable resource management.

Aim 2 summary of research findings

This study explored the utility of using the Google Earth Engine (GEE) geospatial cloud computing platform to process and analyse multi-spectral Sentinel-2 imagery to map land use land cover (LULC) with a particular focus on mapping *Cannabis sativa*. Sentinel-2 images were used to generate 17 spectral indices, selected based on their application frequency and performance in the literature. A composite image was created by calculating the median values of specific spectral bands and indices, which were used for supervised classification of *Cannabis sativa* and other LULC classes. Training data, including ground-truth polygons and visually identified points, were added in GEE to train the classification algorithm based on the unique spectral characteristics of the mapped classes. In general, we found that we were able to map LULC at a relatively high accuracy, capture the spatial heterogeneity within the study region and adequately distinguish between *Cannabis sativa* and other LULC classes. Comparisons between the various classification algorithms on classification accuracy, revealed that the various machine learning algorithms available within GEE performed relatively well at mapping LULC within the study area (OA ≥ 80%).

We also used two methods to evaluate land suitability for dryland production of *Cannabis* using available South African datasets and remote sensing imagery. The first method used the Predictive Analysis Tool (PAT) available in ArcGIS (ESRI, 2014). The methodology assumes that the environmental / bioclimatic conditions of the known locations can be generalised to predict other locations that match those conditions. For the current study, we utilised 28 data layers derived from the Schulze (2007) database, including constraints of rainfall, temperature, aridity index, slope (<12%), and using the *Cannabis sativa* presence data as constraint for PAT modelling. Areas in Eastern Cape and KwaZulu Natal that have slope of <12% and match the range of rainfall, temperature, aridity index characteristics of the *C. sativa* presence data were identified. Notably the predicted areas are very limited but this is due to the constraint of the limited presence data. Since the concern of this study was to identify those areas where dryland cropping is possible without access to irrigation, the modelling approach used the successful dryland growers of the Umzimvubu river valley as presence-only input.

The second method identified suitable growing areas by implementing species distribution modelling in Google Earth Engine. The results from the two approaches used in this modelling study demonstrate that there is limited opportunity in the region for expanding dryland grow sites beyond the Umzimvubu River valley. Although the Suitability Distribution Model suggests a somewhat wider growth area relative to the PAT result, the risks associated with climatic extremes in this wider region during the growing season far outweigh the benefits. Without access to irrigation water to provide emergency irrigation under extreme weather events, the planting of high value cultivars (e.g. Exodus cheese) under dryland conditions will fail regularly and expose legacy farmers to debt.

Aim 3 summary of research findings

The South African government plans to stimulate the production of *Cannabis sativa* on 100 000 ha of abandoned arable land in the communally owned areas of the Eastern

Cape (former Transkei) and KwaZulu-Natal. These arable lands have been cultivated irregularly for >80 years, but have been abandoned in recent years due to land degradation with changes in their chemistry, including a reduction in fertility and acidification. The lands were created on indigenous, natural grasslands, and were part of a project stimulated under the policy recommended by the Tomlinson Commission, to enable the so-called self-governing territories to produce their own food. The project involved the contouring of natural grasslands and the levelling of cultivation beds. Contour banks or 'mounds' comprised the soil and associated organic material that were scraped off the beds. The novel landscape resulting from these historical agricultural policies resulted in two distinctly different landscape components, each with their own unique set of soil and hydrological properties. In order to assess the challenges that growers are likely to encounter in this environment, we designed a field trial in the Eastern Cape to answer several questions about growing *Cannabis* under dryland conditions in this region.The questions focused on differences in soil chemistry associated with the mounds and the cultivation beds and how these differences in chemistry and fertility affect the suitability of these soils, reflected by measured plant attributes (e.g. plant height, leaf area index, stomatal conductance), for cannabis cultivation. In addition, they focused on the water use of the currently dominant grass species in this novel landscape compared with that of a crop of *Cannabis sativa*, as well as the the risks are to growers from local exceptional climatic weather conditions that occur during the crop cycle. The risk of crop failure and the benefits of different types of irrigation infrastructure with emergency irrigation options were considered. Finally, suitable sources of Nitrogen (N) to enrich the degraded soils were considered.

The results confirm that the major differences in the soil characteristics radically affect the performance of *Cannabis sativa*, with the off-mound cultivation beds, which will be the dominant conditions under which *Cannabis* will be grown in communal lands, being much less fertile and having very low pH. Dryland cultivation of abandoned arable lands within the planned region will require a significant injection of financial support to counteract the problem of soil acidification. *Cannabis sativa* has been found to grow best in neutral (pH 7) soil, so copious addition of agricultural lime will be necessary.

Under dryland conditions, with no or limited emergency irrigation, a cannabis crop will result in marginally higher transpiration than the indigenous grassland that it replaces.

We provided organic N in the form of black soldier fly frass in this study. A suitable source of plant available N will need to be sourced. Livestock manure may be a suitable option, but this was not assessed in this study.

The field trial in KwaZulu-Natal focused on a commercially planted area close to Pietermaritzburg. Approximately 7 ha of hemp was planted on 21 November 2022 and harvested on 15 April 2023. Standard microclimatic variables and the volumetric soil water content, plant height and Leaf Area Index (LAI) were measured and water use was monitored using an open path eddy covariance system. The EC measurements indicate that the total ET from the hemp crop over the growing period was 377 mm. The average daily ET was 2.94 mm plant^{-1} or 28.4 L tree^{-1}. The crop factor varied between 0.63 and 0.76 throughout the season and the water productivity of hemp (kg of fresh bud per m^{-3} of water) was 0.96 kg m^{-3}. Hemp had a high water use and low water productivity compared to other international hemp studies. This may be partly due to the higher planting density reported in other international studies (2 000 plants ha^{-1} vs. 300 000 –

2 400 000 plants ha^{-1}). These results provide the first water use and crop factor estimates of hemp in South Africa and provided the data required to assess the streamflow reduction activity of hemp.

Aim 4 summary of research findings

The increased production of hemp for floral (bud), fibre, seed and/or biomass production may result in a land use change that could negatively impact available water resources, even if the crop is rainfed. Hence, an aim of this project was to simulate the (i) yield and water use of hemp cultivation, as well as to (ii) assess the hydrological impact of hemp production on downstream water availability.

The AquaCrop model was selected to meet this aim since (i) parameters exist for hemp fibre and seed production, and (ii) national-scale model runs can be undertaken using an automated procedure that minimises computational complexity. AquaCrop parameters for simulating hemp fibre and seed yield were obtained from the literature, which was used to simulate yield at six locations in Malaysia using 10 years of input climate data. The experimental work undertaken at field and pot scale (cf. Chapters 3-5) focused on floral yield, not fibre, seed or biomass production. Hence, observations and measurements could not be used to fine-tune or validate existing hemp parameters.

Each of the 1 946 quaternary catchments in southern Africa (South Africa, Lesotho and Eswatini) have been disaggregated into three zonal polygons of similar altitude to minimise spatial climate and soil variability. This created 5 838 altitude zones (formerly known as quinary sub-catchments), each with representative soil data and 50 years of daily climate data. AquaCrop was run at a national scale for each altitude zone (AZ), which produced 49 consecutive seasons of simulated data (1950/51-1998/99), from which long-term monthly and seasonal statistics were derived. The model was run for all AZs, including those where rainfed hemp production is economically unviable, due to limited information on where the crop can be successfully cultivated in South Africa. AquaCrop was run in calendar day mode (similar to the Malaysian simulations) for two plant densities namely 150 000 and 75 000 plants ha^{-1} that represent fibre and seed production systems respectively, each with the same planting date (01 December). This equates to over 1.14 million seasonal simulations using daily climate data.

From the modelled results for rainfed growing conditions, national scale maps of attainable fibre and seed yield were produced, as well as crop water productivity of seed production and maximum above-ground biomass production. It is important to note that AquaCrop simulates dry (not fresh) yields, and thus outputs biomass and fibre/seed yield in dry tons per hectare (or dry t ha^{-1}). Fibre yields were lower than seed yields by up to 0.49 t ha^{-1} (spatial average of 0.31 t ha^{-1}), which equates to a relative difference of 15.9-46.6% (36.5% average). These results differ to those for Malaysia, where simulated fibre yields were higher than seed yields by 73%.

For southern Africa, hemp seed yield ranges from 0.14-1.48 t ha^{-1}, with a spatial average of 0.89 t ha^{-1}. Above-ground biomass production ranges from 0.81-10.21 t ha^{-1} (5.80 t ha^{-1} average), which is well below the theoretical maximum of 25 t ha^{-1} for hemp. As expected, the maps highlight the eastern seaboard of the country as being suitable for hemp cultivation. For seed production, the crop is most water use efficient along the coastal and adjacent inland regions of southern KwaZulu-Natal, including the Eastern and Western Cape, i.e. the southern coastal region of the country that experiences all-year rainfall seasonality.

The crop cycle length for seed production was also mapped, which shows one-third of the AZs have a shorter season length (85-114 days) and are likely to be unsuitable for hemp production. Suitable cultivation areas along the eastern seaboard of the country are associated with season lengths of 118-119 days. This narrow range highlights a consequence of running the AquaCrop in calendar day mode and not the preferred growing-degree day mode. Hence, water and temperature stress effects on transpiration were not simulated, and thus AquaCrop over-estimated (i) crop evapotranspiration, (ii) fibre and seed yield, as well as (iii) above-ground biomass production.

The ACRU hydrological model was selected to assess the impact of land use change on hydrological response since it has been used extensively in numerous WRC-funded projects. ACRU was also run nationally for all 5 838 AZs to determine if hemp cultivation is a potential stream flow reduction activity. Since ACRU is particularly sensitive to inputs of monthly crop coefficients, representative values for each AZ were simulated using AquaCrop for unstressed (i.e. artificially irrigated) growing conditions. This approach derived unique crop coefficients for each zone, which is considered more robust than assuming that crop coefficients obtained at a single experimental site over one season, are representative of all other crop growing regions. For the fallow period (May-November), measured crop coefficients that represent weedy conditions were used. Other parameters required by the model to assess runoff production were mostly obtained from the literature.

Runoff generated from rainfed cultivation of hemp biomass was assessed relative to runoff for baseline conditions (i.e. natural vegetation). ACRU parameters for natural vegetation were determined by a previous WRC-funded project. The stream flow reduction potential was calculated as the difference in mean annual runoff (MAR) generated from the crop layer (MAR_{CROP}) and the baseline layer (MAR_{BASE}). The difference in (i.e. $MAR_{DIFF} = MAR_{BASE} – MAR_{CROP}$) was then expressed as a percentage relative to MAR_{BASE}. If it exceeds 10%, the reduction in MAR is considered significant since it may negatively impact downstream water availability. Similarly, if monthly runoff during the driest three months (i.e. low flow period) is reduced by 25% or more, then downstream water users can be adversely affected.

Based on the modelled results, hemp biomass production has the potential to significantly reduce both annual and low flows when compared to natural vegetation. It is therefore recommended that large-scale production of hemp biomass is not conducted in water-stressed catchments. However, it is important to note that the stream flow reduction potential is over-estimated for the following reasons: Firstly, the modelling approach assumes a change in land cover from natural vegetation to crop cultivation across the entire altitude zone, which is unrealistic since other land uses are not considered. Secondly, the approach does not consider runoff "losses" (i.e. reductions) in one catchment can be offset by water "gains" in neighbouring catchments (when $MAR_{CROP} > MAR_{BASE}$). Thirdly, monthly crop coefficients were over-estimated since AquaCrop was run in calendar day mode, as noted previously. Lastly, the stream flow reduction potential of hemp biomass planted at a high density (150 000 plants ha^{-1}) was assessed, which represents the worst-case scenario when compared to the cultivation of seed and especially floral hemp.

It is important to re-iterate that AquaCrop was run in calendar day mode, as was done for Malaysia. AquaCrop does not account for pests and disease impacts on crop growth. Hence, hemp yield (fibre, seed and biomass) and water use (crop evapotranspiration) are over-estimated, including crop cycle length, because transpiration is not reduced by cold temperature stress, nor does hot/cold temperature stress inhibit pollination or decrease HI. A very low number of seasons with zero yield (i.e. crop failures) were simulated as a result of running AquaCrop in calendar day mode. Therefore, the maps of seed yield and biomass production are more useful in showing relative differences between altitude zones than actual values likely to be attained in each zone.

Aim 5 summary of research findings

The stakeholder analysis explored the socio-economic dynamics of cannabis cultivation in Mpondoland, Eastern Cape. It focuses on understanding the challenges and opportunities faced by legacy farmers in the evolving cannabis industry. The following are the key findings:

- Legacy farmers face significant barriers to participating economically in the cannabis market.
- Current regulatory frameworks limit local economic development.
- There is substantial potential for sustainable, community-driven cannabis cultivation.
- Stakeholders show strong interest in collaborative approaches to industry development.

The key recommendations from this work are as follows:

- Develop clear, supportive legal pathways for small-scale cannabis cultivation.
- Create comprehensive programs for market access and skills development.
- Establish a multi-stakeholder approach to industry growth.
- Prioritize sustainable and ecological cultivation practices.

Capacity building of students and institutions

The project supported four students – three MSc students and a PGDip student. Besides these students, the WRC project led to significant institutional and researcher capacity building on *Cannabis* water use.

Capacity building at the community level

The stakeholder engagement conducted by Mr Botha resulted in capacity building of the community supported by the Eastern Cape Township Cannabis Incubator in Mthatha. The community had strong interest in adopting sustainable practices and Mr Botha shared information sheets with explanations of how to make one’s own black soldier fly frass and mycorrhizal fungi inoculum. In addition, fact-sheets on how to grow cannabis in dry-land conditions created by Anthony Palmer, were translated into isiXhosa and shared with the participants.

Key recommendations for future research from the project

- **Increase In-Situ Data Collection** – Improve model accuracy by incorporating more ground-truth data to refine *Cannabis* value chain analysis.
- **Extend Climate Database** – Update the Altitude Zones Climate Database with at least 20 years of daily observations to reflect climate change impacts.
- **Conduct Field Experiments** – Gather data on yield, biomass, and water use under both irrigated and rainfed conditions across multiple agro-ecological zones.
- **Improve Crop Modelling** – Convert crop phenology observations to Growing Degree-Days (GDDs) and assess crop failure risk to enhance model reliability.
- **Develop Land Suitability Maps** – Use AquaCrop simulations to map suitable areas for *Cannabis* cultivation based on different product types (biomass, fibre, seed, floral buds).
- **Assess Water Impact** – Conduct further research to determine if *Cannabis* should be classified as a Stream Flow Reduction Activity (SFRA), potentially leading to cultivation restrictions.
- **Optimize Planting Dates** – Expand model simulations to test multiple planting dates (September–January) to understand their impact on crop yield.
- **Perform Economic Analysis** – Conduct cost-benefit studies, including security costs, to evaluate the financial viability of *Cannabis* cultivation in South Africa.
- **Enhance Socio-Economic Support** – Develop legal pathways for small-scale growers, improve market access, and promote sustainable farming practices.
- **Strengthen Policy and Market Development** – Establish legislation, support seed quality control, facilitate farmer cooperatives, and explore economic diversification opportunities like *Cannabis* tourism and niche cash crops.

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Acronyms

ACIAR	Australian Centre for International Agricultural Research
ACRU	Agricultural Catchments Research Unit
AD	Anno Domini
ANOVA	Analysis of Variance
ARC	Agriculture Research Council
AUC-PR	Area Under the Precision-Recall Curve
AUC-ROC	Area Under the Curve of the Receiver Operator Characteristic
AZ	Altitude Zone
BCE	Before Common Era
CART	Classification and Regression Tree
CBC	Cannabichromene
CBD	Cannabidiol
CBG	Cannabigerol
CBN	Cannabinol
CC	Canopy Cover
CEF	Controlled Research Facility
CGC	Canopy Growth Coefficient
CSIR	Council for Scientific and Industrial Research
CWP	Crop Water Productivity
CWRR	Centre for Water Resources Research
d.f	Degrees of Freedom
DAFF	Department of Agriculture, Forestry and Fisheries (now DFFE)
DFFE	Department of Forestry, Fisheries and the Environment
DM	Dry Matter
DSS	Decision Support System
DWS	Department of Water and Sanitation
ECRDA	Eastern Cape Rural Development Agency
ET	Evapotranspiration
FAO	Food and Agricultural Organisation (of the United Nations)
GDD	Growing Degree-Day

GEE	Google Earth Engine
GTB	Gradient Tree Boosting
GUI	Graphical User Interface
GVC	Global Value Chain
H	Sensible heat flux
HI	Harvest Index
HVB	High Value Beef project
IEJ	Institute for Economic Justice
ILHAM	Institute for Land and Agricultural Management
IWR	Institute for Water Research
KZN	KwaZulu-Natal
LAI	Leaf Area Index
LAS	Large Aperture Scintillometer
LCF	Leaf Chamber Fluorometer
LE	Latent heat flux
LULC	Land Use Land Cover
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
MAR_{BASE}	Mean monthly and annual runoff (MAR) response for baseline conditions
MAR_{CROP}	Mean monthly and annual runoff (MAR) response for crop
MAXENT	Maximum Entropy
MSI	MultiSpectral Instrument
NAMC	National Agricultural Marketing Council
NCMP	National Cannabis Masterplan Process
NIR	Near Infrared
NPO	Non-Profit Organisation
NWA	National Water Act
OA	Overall Accuracy
OTDM	Oliver Tambo District Municipality
PA	Producer Accuracy

PAR	Photosynthetically active radiation
PAT	Predictive Analysis Tool
PC	Pot Capacity
PET	Potential Evapotranspiration
PWUEc	Canopy Photosynthetic Water Use Efficiency
QC	Quality Checks
R	Programming language and open-source software
RF	Random Forest
RGB	Red, Green and Blue
RH	Relative humidity
RMSE	Root Mean Square Error
ROI	Region of Interest
RU	Rhodes University
SA	South Africa
SANBI	South African National Botanical Institute
SC	Stomatal Conductance
SCS	Soil Conservation Service
SDM	Species Distribution Modelling
SEDA	Small Enterprise Development Agency
SFRA	Stream Flow Reduction Activity
SLN	Specific Leaf Nitrogen
SME	Small and Medium Enterprise
SMME	Small, Medium and Micro-Enterprise
SRTM	Shuttle Radar Topography Mission
SVM	Support Vector Machine
SWC	Soil Water Content
THC	Tetrahydrocannabinol
THCV	Tetrahydrocannabivarin
TTR	Thornley Transfer and Resistance
UA	User Accuracy

UKZN	University of KwaZulu-Natal
USDA	United States Department of Agriculture
VC	Value Chain
VI	Vegetation Index
VPD	Vapour Pressure Deficit
VWC	Volumetric Water Content
WoS	Web of Science
WP	Water Productivity
WRC	Water Research Commission
WUE	Water Use Efficiency
WUEi	Intrinsic Water Use Efficiency
WUEins	Instantaneous Water Use Efficiency

CHAPTER 1 PROJECT BACKGROUND AND LITERATURE REVIEW

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This chapter provides a brief introduction to *Cannabis sativa* to set the context for the problem statement and the scope of the research (section 1.1). Section 1.2 provides the scoping literature review and bibliometric analysis, followed by an overview of the structure of the report under section 1.3.

1.1 Introduction

Interest in *Cannabis sativa* is growing globally and in South Africa, and the reasons for this are varied as it is a multipurpose crop that can be grown for fibre, seed, oil and medicinal properties. Hemp and marijuana both come from the same family *C. sativa*, with the difference being that hemp has a tetrahydrocannabinol (THC) content of less than 0.3% and is typically cultivated for fibre or seeds.

Hemp is one of the oldest cultivated crops (Sawler et al., 2015), and has become one of the most important fibre crops both in South Africa and globally as its uses are vast. Its fibre is used in the clothing and textile industries, paper and compressed wood products, and cosmetics. More recently, there has been interest in using it in the energy sector (biomass and bioenergy) from a sustainable development perspective. Other environmental benefits include phytoremediation and carbon sequestration. The phytoremediation potentials of hemp in restoring and remediating land polluted by heavy metals has been demonstrated (Adesina et al., 2020). Hemp has also been shown to capture more CO_2 per hectare than other commercial agricultural crops, including forests, making it a promising carbon sink (Adesina et al., 2020). However, the association of hemp with marijuana and the legal requirements (since 1903 when 'dagga' prohibition was passed) for growth have limited widespread cultivation of it in South Africa, and the country is currently a net importer of hemp fibre and seeds (Department of Agriculture Forestry & Fisheries, 2011). Given that *C. sativa* is the most extensively trafficked and sought-after illicit drug worldwide (UNODC, 2011; Houmi et al., 2018), the restrictions on any form of cultivation are necessary. More recently, however, a number of countries globally, starting with Uruguay and then Canada, have fully legalized cannabis as well as Colorado State in the USA. A driver for the legalisation of all aspects of the cannabis value chain are the perceived tax revenue benefits that will result, as well as other economic spinoffs of investment and employment.

Under South African legislation, cultivation of *C. sativa* for commercial purposes, regardless of the THC content, requires a license issued by the South African Health Products Regulatory Authority and a permit issued by the Director General of the National Department of Health in terms of section 22A(9)(a) (i) of the Medicines Act (1995). The exception is cultivation of *C. sativa* privately for an adult's personal consumption. Cannabis for Private Purposes Act (CfPPA) 7 of 2024 was passed in June 2024 Cannabis for Private Purposes Act 7 of 2024 (English / Sepedi) | South African Government. It covers the following aspects:

- respect the right to privacy of an adult person to use or possess cannabis;
- regulate the use or possession of cannabis by an adult person;
- provide for an alternative manner by which to address the issue of the prohibited use, possession of, or dealing in, cannabis by children, with due regard to the best interest of the child;
- prohibit the dealing in cannabis;
- provide for the expungement of criminal records of persons convicted of possession or use of cannabis or dealing in cannabis on the basis of a presumption;
- amend provisions of certain laws; and
- provide for matters connected therewith.

1.1.1 Problem statement

Cannabis sativa is the most extensively trafficked and sought-after illicit drug worldwide (Houmi et al., 2018; UNODC - United Nations Office on Drugs and Crime, 2011). This has led to a great deal of interest in mapping *C. sativa* to rapidly and more efficiently detect the growth of illicit plantations which can then be destroyed, ultimately resulting in reduced consumption (Lisita et al., 2013). However, perceptions regarding the use of *C. sativa* continue to evolve, particularly around its use for medicinal purposes.

The potential economic benefits, amongst other factors, are driving the debate around legalisation in South Africa currently. There is much anecdotal evidence that *C. sativa* cultivation, particularly in the Eastern Cape and KwaZulu-Natal provinces, by small-scale farmers is widespread, where it is intercropped with food crops. Given this, the presumption is that a fair knowledge exists on successful cultivation practices, and thus *C. sativa* could be a feasible, high-value crop for emerging small-scale farmers.

Despite the potential benefits, economic and environmental, the water use of *C. sativa* remains largely unknown beyond the understanding that it is a water thirsty plant (Ashworth and Vizuete, 2017). The water use, or total evaporation of *C. sativa* has not been measured for growing conditions in South Africa, and estimates in the international literature are nearly non-existent.

Given the growing interest in and promotion of *C. sativa* cultivation in South Africa, the need to determine the water use of this crop and the associated impacts on hydrological response has become critical. Understanding the water use and related impacts will allow for informed decisions regarding *C. sativa* cultivation to be taken and will prevent adverse impacts on already stressed water resources.

1.1.2 Project aims and scope

The project aims to produce new knowledge and information to guide a growing interest in *C. sativa* in response to the changing legal and regulatory requirements as well as an increasing drive to follow environmentally sustainable development pathways (e.g., bioenergy). The South African National Water Act (No. 36 of 1998) mandates the regulation of land-based activities that reduce streamflow by declaring them streamflow reduction activities (SFRAs). The project was motivated with the knowledge that while it is widely known that *C. sativa* is a water-intensive crop, no actual measurements of its water use existed in South Africa and therefore its streamflow reduction cannot be determined.

1.2 *Cannabis* scoping literature review and bibliometric analysis

1.2.1 Brief review of Cannabis sativa growing conditions

This section briefly reviews some of the relevant literature for the variation in *C. sativa* characteristics with a focus on arid and semi-arid growing conditions. These variables and ranges were used as guidance for the project.

Published work on field-grown *Cannabis* crops is limited in scope, typically focused on one location and a few cultivars, and currently, the results are insufficient to confidently support crop production and optimization in semi-arid systems. There is an indication that this is changing with more recent literature reporting more measured and controlled variables (Cosentino et al., 2012; García-Tejero et al., 2014; Struik et al., 2000).

> Although hemp is well adapted to the temperate climatic zone and will grow under varied environmental conditions, it grows best under warm growing conditions, an extended frost-free season, highly productive agricultural soils, and abundant moisture throughout the growing season.

The growing conditions of *Cannabis sativa* vary widely from region to region and are controlled by various parameters or factors from the genetics of the plant, temperature, soil moisture, soil pH, wind, relative humidity, radiation, time of planting and harvesting (de Prato et al., 2022; Desanlis et al., 2013). The plants perform differently in temperate regions like Europe and the USA compared to the tropics and subtropics like Australia (de Prato et al., 2022). In the Northern Hemisphere, the plant must be planted below 50˚N while in the Southern Hemisphere, the range is unknown due to lack of research in this field as a result of its legal status and financial constraints in this region (Chandra et al., 2017). The little available information comes mostly from Europe and America, although there is a burgeoning but limited research sector in Australia and China. Notably, indoor growing conditions are different from outdoor conditions, with indoor facilities generally applying more inputs (Denton et al., 2001). A good example is the use of root hormones applied to cuttings before they are sown into the soil during indoor cultivation (Chandra et al., 2017), while many outdoor cultivations try to use as little inputs as possible.

The contemporary production of *Cannabis* is dominated by the Northern Hemisphere (Figure 1-1). Data from the Food and Agriculture Organisation (FAO) for the years 1961 to present consistently showed Chile as the only recorded country in the Southern hemisphere with seed and fibre production (FAO, https://www.fao.org/faostat).

1.2.2 Product types

Medical and pharmacological production

Cannabis has recreational and medicinal use (Warf, 2014), and focus within the health care sector is rapidly growing on account of its promising properties (Żuk-Gołaszewska and Gołaszewski, 2018). The medicinal and therapeutic properties of cannabis and its derivatives are being widely researched, but are currently still poorly understood due to the legacy of the legal status in many modern societies (Bridgeman and Abazia, 2017). Preclinical research has demonstrated that medicinal cannabis delivers health benefits, and the effectiveness of the first cannabis-based medication has been confirmed (Adler and Colbert, 2013).

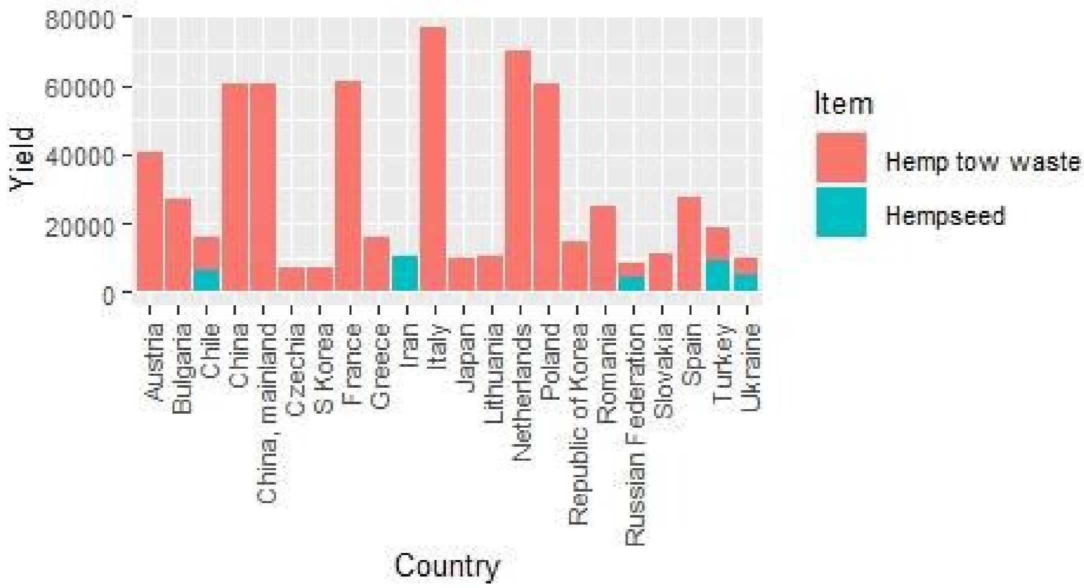


Figure 1-1 Countries growing Cannabis for fibre and seed production in the year 2020. Data was collected from the FAO (https://www.fao.org/faostat)

The cannabinoids and oil products of interest are metabolites thought to have an important role in increasing the plant fitness to the environment (Lipson Feder et al., 2021). The metabolites are found in all parts of the plant (Table 1-1) and the observed dynamics of the accumulation during flower development and fertilization points to their different roles along the plant's life cycle (Andre et al., 2016). Suggested roles for the metabolites include defence against biotic or abiotic factors, protection from UV radiation, prevention of desiccation, or induction of cell death in leaves (Huchelmann et al., 2017 and references therein).

Grain is harvested from pollinated females and is used to produce hemp seed products high in oils and protein (Wang and Xiong, 2019). Only the unpollinated female flowers are useful for CBD production, with these flowers producing the highest concentration of all the cannabinoids including CBD, when compared to the leaves and other parts of the plant (Wellhoffer, 2020). The use of feminized seeds or cuttings propagated from female plants is preferred, as it eliminates labour and wasted resources of growing and scouting for male plants to be removed (Toth et al., 2020).

*Table 1-1 Cannabinoids are found in different plant parts in both drug-type and fibre-type varieties (Andre et al., 2016). *Full names are provided in the footnote.*

Plant part	THC*	CBD*	CBN*	CBG*	THVC*	CBC*
Fine roots	Y	Y	-	Y	-	-
Roots	-	Fibre	-	-	-	-
Seed	Fibre Drug	Fibre Drug	Fibre Drug	-	-	-
Stem	Fibre Drug	Fibre	Fibre	-	-	-
Leaves	Fibre Drug	Fibre Drug	Drug	Fibre Drug	-	-
Pollen	Drug	Drug	Drug	Drug	Drug	Drug
Flower	Fibre Drug	Fibre Drug	Drug	Fibre Drug	Fibre Drug	Fibre Drug

*THC - tetrahydrocannabinol, CBD - cannabidiol, CBN - cannabinol, CBG – cannabigerol, THCV -tetrahydrocannabivarin, CBC - cannabichromene

Cannabinoids are used to alleviate symptoms of certain diseases, such as nausea and vomiting in cancer patients who are undergoing chemotherapy in many countries around the world (Malik et al., 2020). The authors hypothesised that CB1 (Cannabinoid receptor) is responsible for alleviating these symptoms since the inactivation of CB1 leads to vomiting, and when *Cannabis* is administered, this receptor is activated; thus, nausea and vomiting are treated or inhibited.

Cannabis is used to alleviate pain caused by several conditions such as cancer, HIV, diabetes, arthritis, and multiple sclerosis. It can reduce spasms in patients suffering from multiple sclerosis and be used to treat people suffering from epilepsy, but further studies need to be conducted to obtain conclusive results (Corey-Bloom et al., 2012; Stockings et al., 2018). Naftali et al. (2013) state that *Cannabis* has anti-inflammatory properties and helps alleviate many conditions, including Crohn's disease.

Studies also found that *Cannabis* can inhibit the growth of tumours by facilitating apoptosis (cell death), thus preventing some cancers from forming (Pisanti et al., 2007). Preliminary studies on the medicinal benefits of Cannabis illustrate that it can alleviate or treat some conditions despite the limited research in this field.

Fibre production

In South Africa, the propagation of hemp varieties for agricultural and industrial purposes is limited to plants with a THC content which does not exceed 0.2% (Department of Agriculture Land Reform and Rural Development Republic of South Africa, 2023). Elsewhere in the world, a <0.3% limit is stipulated. In fibre and grain production, male and female plants are allowed to populate the same field, as pollination needs to occur for grain/seed production.

Hemp cultivars are useful in both oil and fibre production. A hemp plant has an outer ring of long fibres called phloem (Cherney and Small, 2016). These fibres are the highest value fibres that can be harvested. The interior fibres, the xylem, are shorter than the phloem fibres which decreases the value of the fibres (Whitmer, 2020). The harvested fibre is used in a variety of products, ranging from textiles, fibre-reinforced concrete (Jarabo et al., 2012), and composite plastics (Panthapulakkal and Sain, 2007).

Westerhuis et al. (2019) strongly advise against “dual use” hemp production for high-quality products and to focus on either seed or textile fibres (from primary fibres running from the bottom to the top of the stem). Further support for this view is that while both male and female plants are used for fibre production, male plants have higher quality yield due to the increased length of the phloem (bast fibres) compared to female plants (Schluttenhofer and Yuan, 2017).

1.2.2 Bibliometric analysis results

An exploratory systematic literature review revealed no publications on water use efficiency in South Africa.

Extraction of data from abstract and citation databases

The bibliometric database was compiled by searching the terms Cannabis or Hemp or Marijuana or Dagga and ("water use" or "water use efficiency" or "evapotranspiration" or yield or agriculture) for the period 2010-2021 in article titles, abstracts and key words on the Scopus and Web of Science (WoS) databases.

The Scopus search returned 1,295 results, whereas the WoS search returned approximately 34,000 results. For the sake of demonstration purposes and brevity, only the first 2,500 results (results listed in order of relevance) were extracted from the WoS search.

Bibliometric Analysis using R and the Biblioshiny App

The Scopus and WoS databases were imported into R statistical software for pre-processing prior to their use in the Biblioshiny App (Aria and Cuccurullo, 2017). These databases were first merged into a single database, thereafter duplicate records were removed, and the database was converted into a “.xlsx” file format that could be imported directly into Biblioshiny.

Biblioshiny is a (non-coders version) web-based application for the bibliometrix package in R. The Biblioshiny App and bibliometrix package in R are open-source tools which can be used to perform comprehensive bibliometric analyses of scientific literature. The merit of utilizing Biblioshiny for such analyses is that both experienced coders and novice users can leverage the capabilities of the bibliometrix package in a user-friendly web-based graphical user interface environment.

The figures and table below were produced by a scoping bibliometric analysis (Table 1-2). The figures indicate the increasing number of scientific outputs and yearly citations from 2010 to 2021 (Figure 1-2, Figure 1-3). The top influential sources of information from environmental and agricultural science journals are shown in the following three figures. Figure 1-7 shows that South Africa is lagging behind in articles published. The wordcloud in Figure 1-9 and Figure 1-10 highlight the keywords and trending topics.

Table 1-2 Bibliometric analysis output example showing a summary of the combined Scopus and Web of Science database for Cannabis research, based on the search terms for the period 2010-2021

MAIN INFORMATION ABOUT DATA	Results
Timespan	2010:2021
Sources (Journals, Books, etc)	1514
Documents	3665
Average years from publication	4.04
Average citations per documents	14.59
Average citations per year per doc	2.51
References	106009
DOCUMENT TYPES	
Article	2389
article; book chapter	94
article; early access	48
article; proceedings paper	13
Book	2
book chapter	39
book review	8
conference paper	135
conference review	4
Correction	3
data paper	1
Editorial	3
editorial material	266
editorial material; book chapter	2
editorial material; early access	6
Erratum	2
Letter	78
letter; early access	1
meeting abstract	100
news item	13
Note	7
proceedings paper	38
Review	398
review; book chapter	4
review; early access	8
short survey	3
DOCUMENT CONTENTS	
Keywords Plus (ID)	12619
Author's Keywords (DE)	7369
AUTHORS	
Authors	10715
Author Appearances	15262
Authors of single-authored documents	334
Authors of multi-authored documents	10381

AUTHORS COLLABORATION	
Single-authored documents	393
Documents per Author	0.34
Authors per Document	2.92
Co-Authors per Documents	4.16
Collaboration Index	3.17

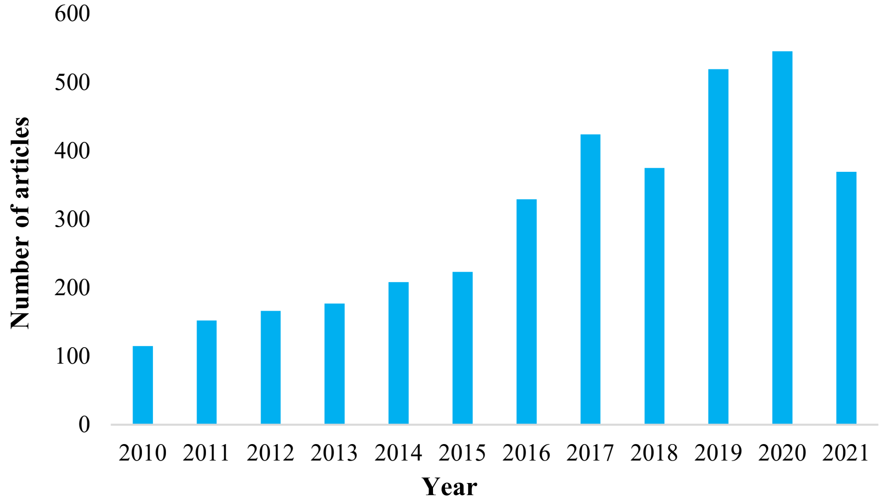


Figure 1-2 Bibliometric analysis output example showing annual scientific production per year between 2010 and 2021

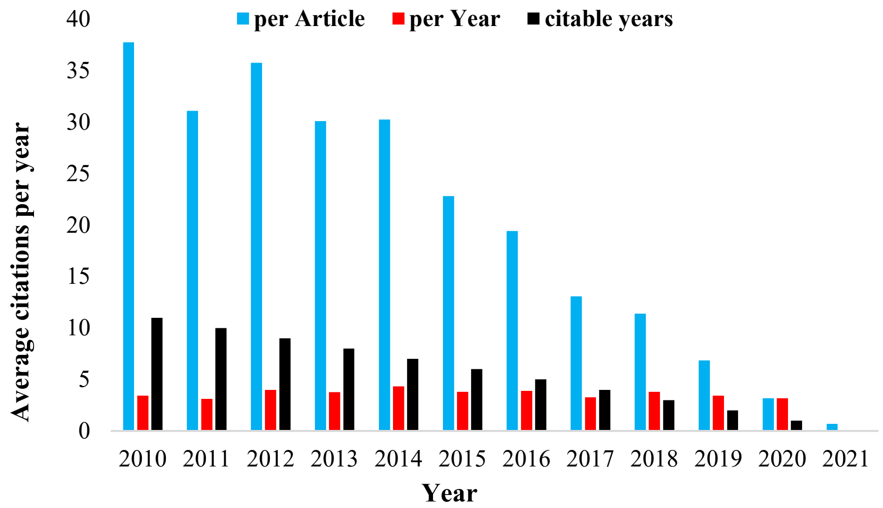


Figure 1-3 Bibliometric analysis output showing the average citations per year and article

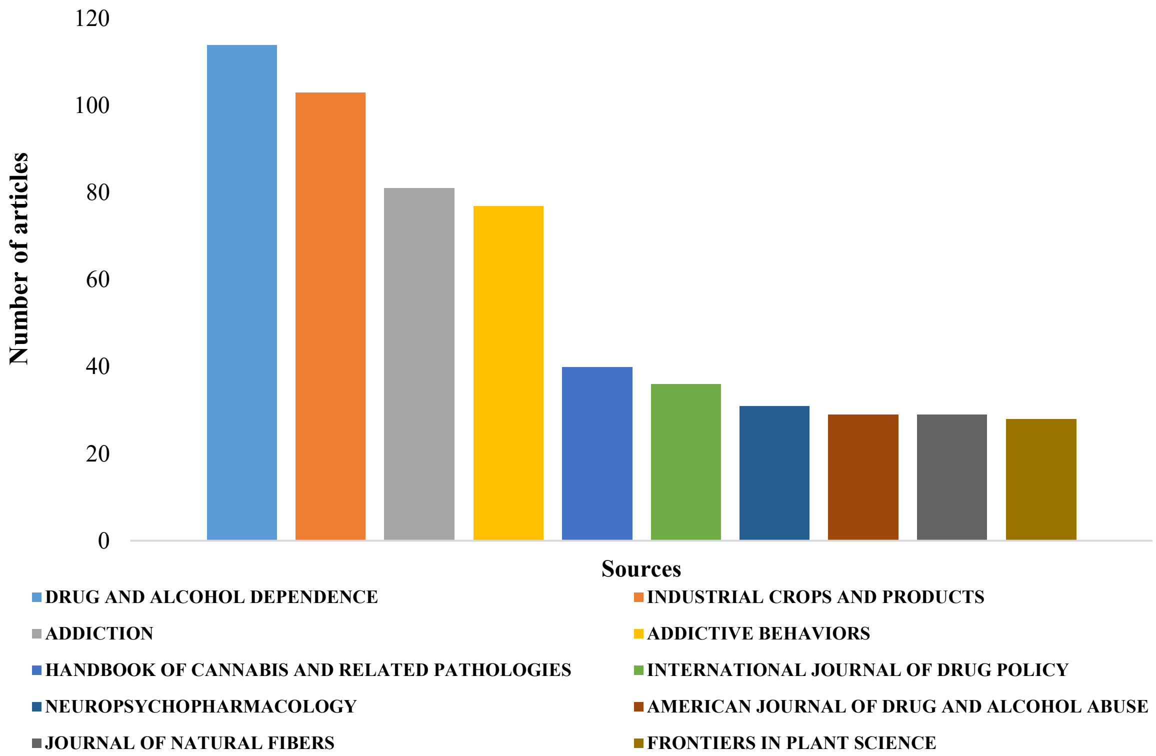


Figure 1-4 Bibliometric analysis output showing the top ten most relevant sources

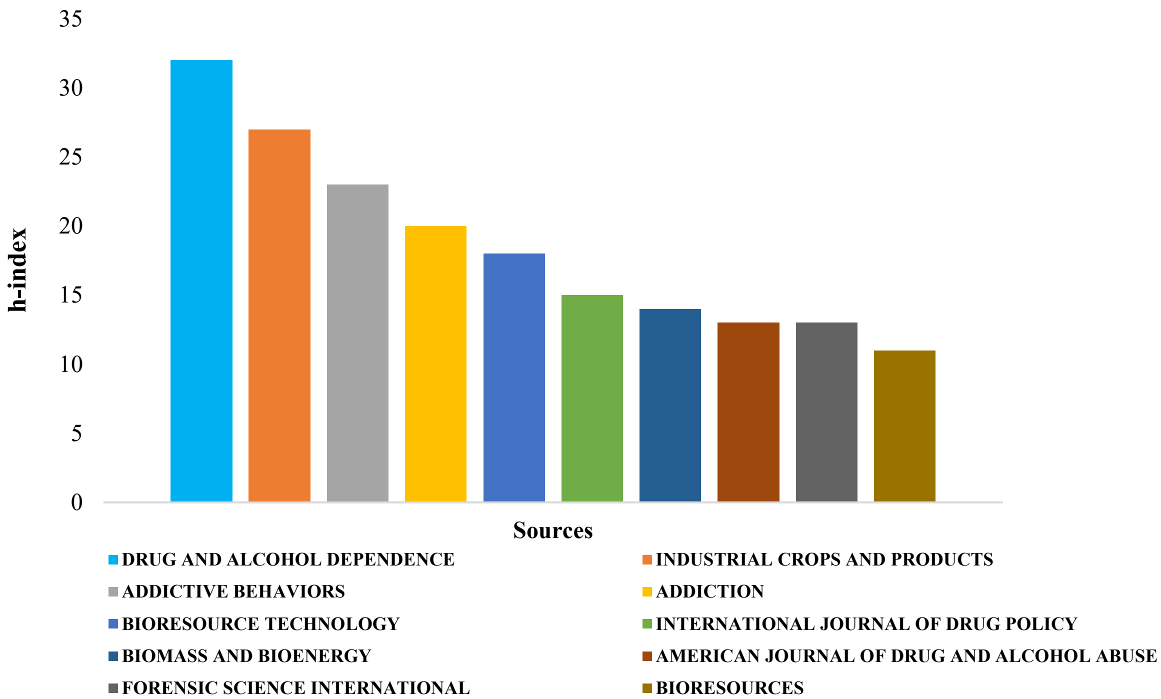


Figure 1-5 Bibliometric analysis output example showing the top ten most influential sources by h-index

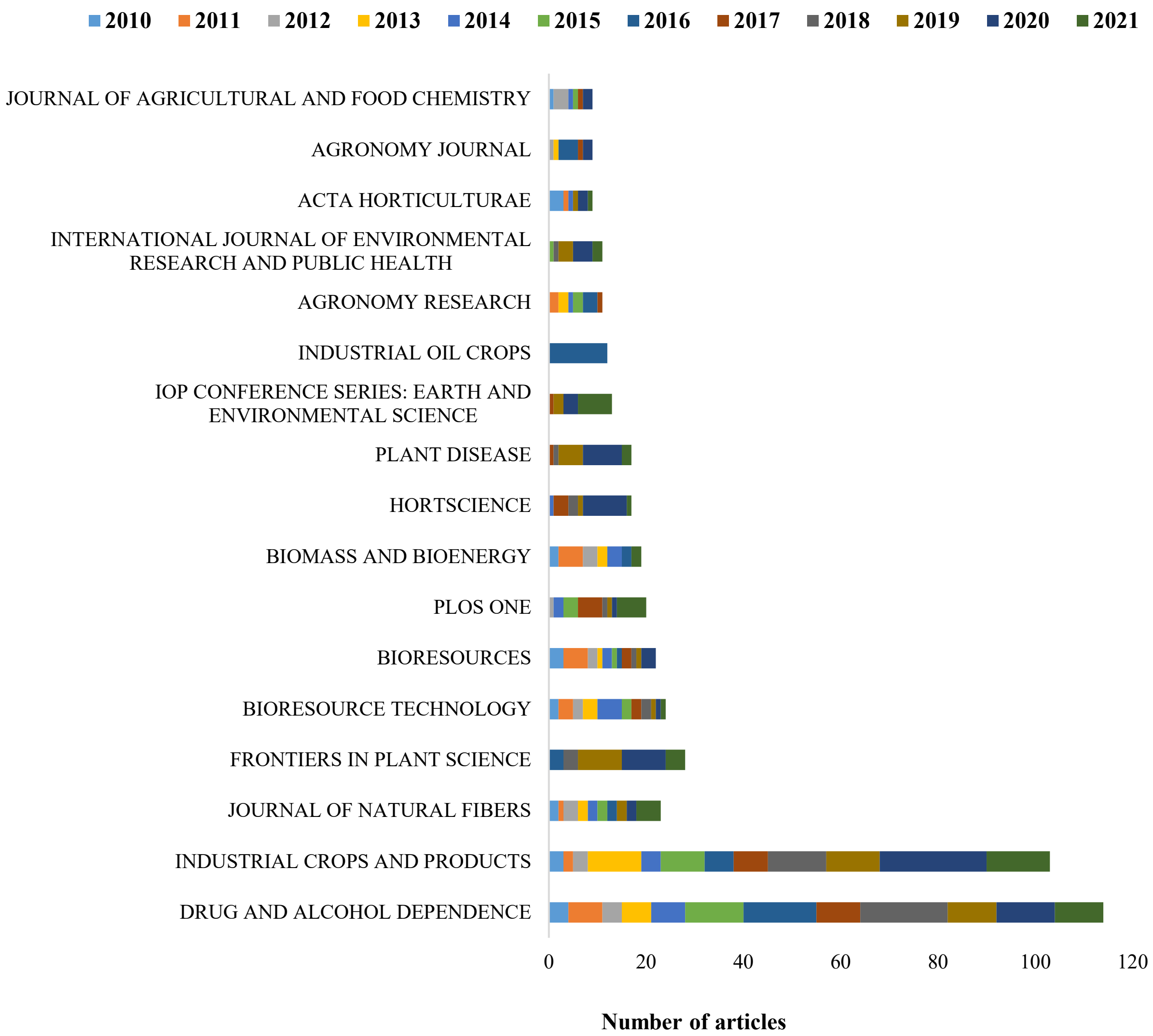


Figure 1-6 Source dynamics showing the number of Cannabis related articles published in environmental and agricultural science journals relative to the journal that has published the most Cannabis related research since 2010

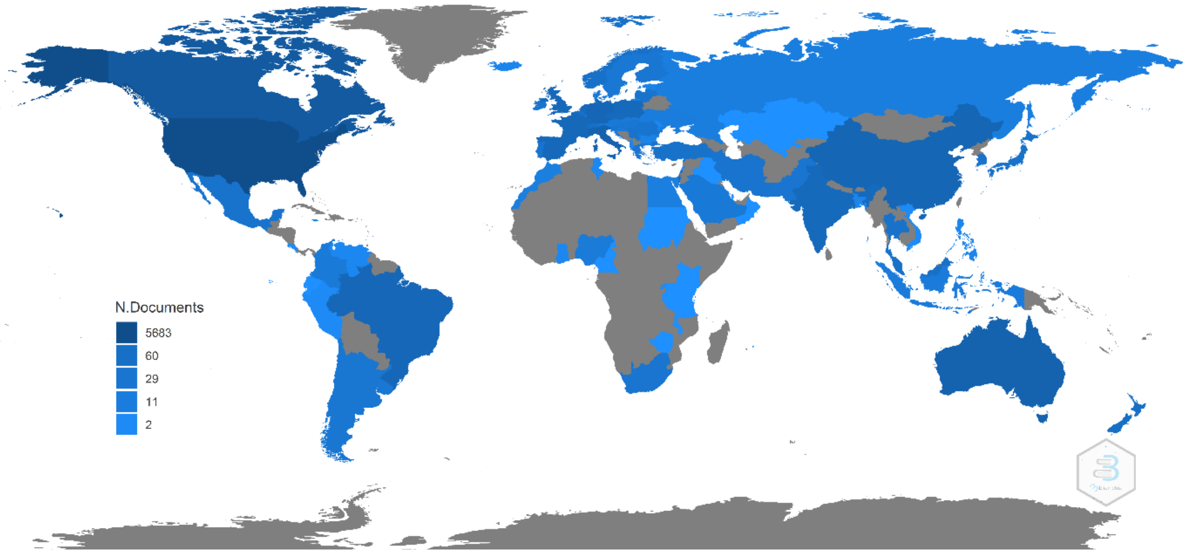


Figure 1-7 Number of articles published per country since 2010, with a total of 31 articles published within South Africa

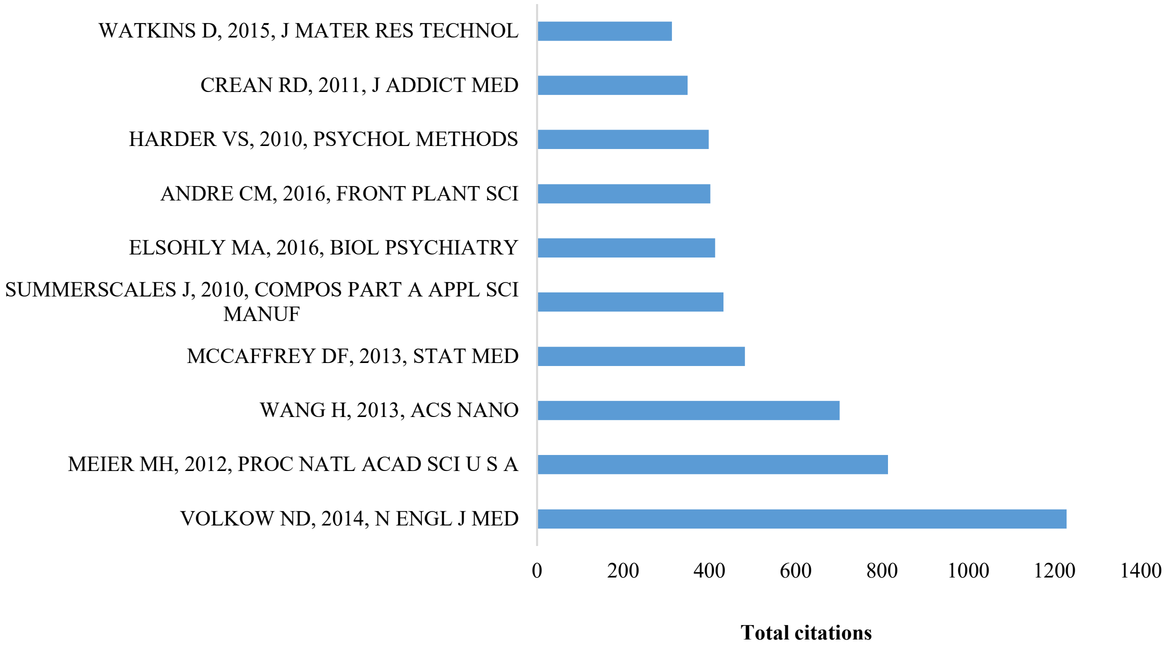


Figure 1-8 Top ten most cited articles

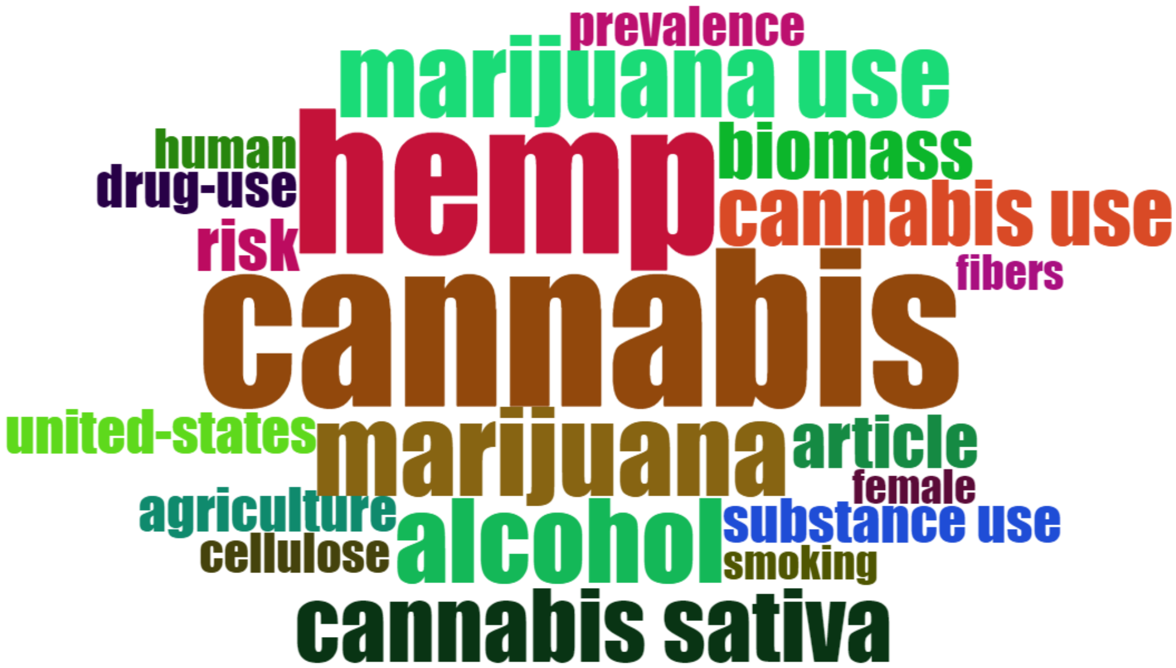


Figure 1-9 Wordcloud representing the top 20 most used keywords within the bibliometric database

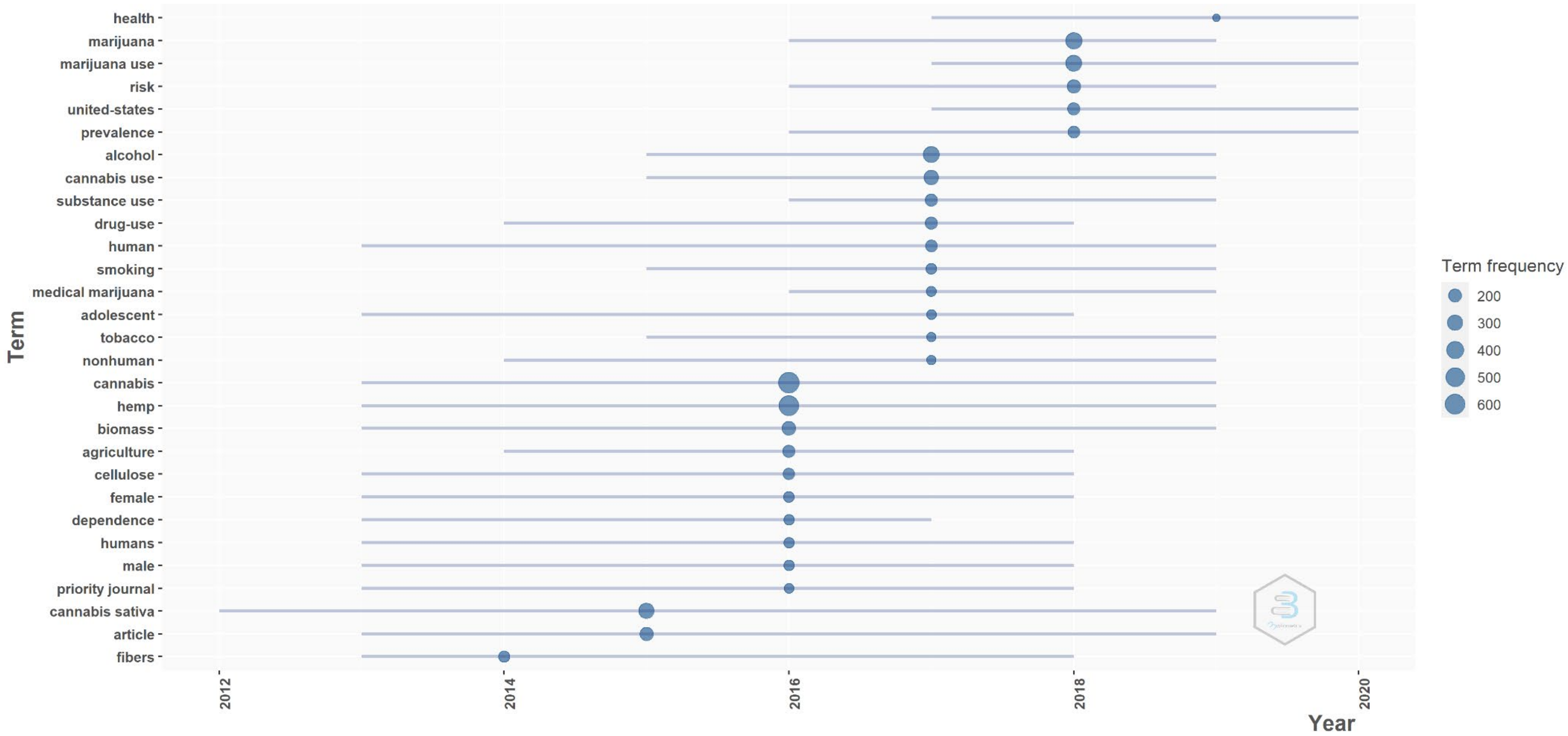


Figure 1-10 Trending topics, summarized using a minimum word frequency of 100 and 10 words per year

1.3 Structure of this report

The report is structured around the five project aims which are as follows:

1. To conduct a scoping review of available literature on the water use, distribution and agronomic management and value chain of *C. sativa* crops for both fibre and oil production (current Chapter 1)
2. To map the extent and distribution of *C. sativa* stands as well as identify suitable growth areas (Chapter 2)
3. Determine the water use and yield of *C. sativa* for either fibre or oil production using field-based measurements (Chapters 3, 4, 5)
4. Undertake multi-scale modelling of the water use, yield and potential hydrological impacts of *C. sativa* (Chapter 6)
5. Undertake a preliminary socio-economic feasibility assessment based on value chain principles including suitable areas for growth and best management practices (Chapter 7)

This chapter covers Aim 1, with an introduction and a bibliometric analysis, and is derived from project Deliverables 1 and 2. Literature review related to Aims 2 to 5 are spread throughout the report under each of the following four chapters.

Chapter 2 provides the background into land suitability mapping and a summary of some of the important variables that affect *Cannabis sativa* growth that are relevant for mapping (Aim 2; based on Deliverables 3 and 4). The chapter presents the methods for mapping using two methods ArcGIS Predictive Analysis Tool and Species Distribution modelling using Google Earth Engine.

Chapters 3, 4 and 5 provide summaries of research by three Masters students who conducted water use measurements of *Cannabis* (Aim 3) in KwaZulu-Natal (Mr Gary Denton and Ms Sindiswa Mbelu) and in the Eastern Cape (Mr Kamva Zenani) using various field and pot experiments. These chapters are based on Deliverables 5 and 6.

Chapter 6 provides results of multi-scale modelling of the water use, yield and potential hydrological impacts of *C. sativa* (Aim 4; based on Deliverable 6 and additional work not reported previously).

Chapter 7 provides details of the stakeholder engagement conducted with stakeholders who provide insights into preliminary information relevant for a socio-economic feasibility assessment (Aim 5; based on Deliverable 7 and additional work not reported previously). This work was primarily conducted by the Rhodes University PGDip student, Mr Jamie Botha.

Finally, Chapter 8 presents recommendations for future research coming out of the project.

1.4 References

ADESINA I, BHOWMIK A, SHARMA H and SHAHBAZI A (2020) A review on the current state of knowledge of growing conditions, agronomic soil health practices and utilities of hemp in the United States. 1. April 2020. MDPI AG. https://doi.org/10.3390/agriculture10040129

ARIA M and CUCCURULLO C (2017) bibliometrix: An R-tool for comprehensive science mapping.

ASHWORTH K and VIZUETE W (2017) High Time to Assess the Environmental Impacts of Cannabis Cultivation. 7. March 2017. American Chemical Society. https://doi.org/10.1021/acs.est.6b06343

CHERNEY JH and SMALL E (2016) Industrial Hemp in North America: Production, Politics and Potential. Agronomy **6** (4). https://doi.org/10.3390/agronomy6040058.

DEPARTMENT OF AGRICULTURE FORESTRY & FISHERIES (2011) A Profile of the South African Hemp Market Value Chain. HEMPMVCP2011-12.

DEPARTMENT OF AGRICULTURE LAND REFORM AND RURAL DEVELOPMENT REPUBLIC OF SOUTH AFRICA (2023) Amendments of the Guidelines of Hemp Cultivation (Low THC Cannabis) for Agricultural and Industrial Purposes made in TERSM Plant Improvement Act, 1976 (Act no. 53 of 1976). 2023. URL: https://www.dalrrd.gov.za/index.php/component/content/article/319-hemp-low-thc-cannabis-regulatory-system

HELLBERG S (2020) Scarcity as a means of governing: Challenging neoliberal hydromentality in the context of the South African drought. Environment and Planning E: Nature and Space **3** (1) 186–206. https://doi.org/10.1177/2514848619853551.

HOUMI M, MOHAMADI B and BALZ T (2018) A hyperspectral based method to detect Cannabis plantation in inaccessible areas. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLII–3 547–551. https://doi.org/10.5194/isprs-archives-XLII-3-547-2018.

LISITA A, SANO EE and DURIEUX L (2013) Identifying potential areas of *Cannabis sativa* plantations using object-based image analysis of SPOT-5 satellite data. International Journal of Remote Sensing **34** 5409–5428. https://doi.org/10.1080/01431161.2013.790574.

SAWLER J, STOUT JM, GARDNER KM, HUDSON D, VIDMAR J, BUTLER L, PAGE JE and MYLES S (2015) The genetic structure of marijuana and hemp. PloS one Public Library of Science **10** (8) e0133292.

UNODC - UNITED NATIONS OFFICE ON DRUGS AND CRIME (2011) World Drug Report 2011. United Nations Publication, Sales No: E.11.XI.10.

CHAPTER 2 MAPPING *CANNABIS* DISTRIBUTION

Authors: Shaeden Gokool, Sukhmani Mantel, Anthony Palmer

2.1 *Cannabis sativa* mapping using remote sensing

Satellite-earth observation data is one of the primary sources of land use land cover (LULC) information (Sidhu et al., 2018). Several studies have demonstrated how the use of hyperspectral and/or multispectral satellite-earth observation data can be used to successfully map different vegetation genera and species, including *Cannabis sativa* (Sibandze, 2010; Houmi et al., 2018; Shelestov, 2017; Sidhu et al., 2018; Ferreira et al., 2019). The use of hyperspectral imagery for mapping *Cannabis sativa* can prove to be advantageous as the higher spectral resolution of these datasets allows for more detailed spectral variations to be captured making it easier to distinguish between different vegetation genera or species, particularly those that may only have marginal differences in their spectral reflectance (Peerbhay et al., 2013; Peerbhay et al., 2014).

However, the high costs associated with the aforementioned datasets and their spatial limitations (low swath width and pixel resolution) may limit their feasibility (Rajah et al., 2018b). Similarly, the high costs associated with the application of new generation multispectral datasets (e.g. IKONOS, World-View and Rapid Eye) may put these datasets out of reach for numerous researchers, even though their high spatial resolution may prove to be quite beneficial for mapping *Cannabis sativa* (Rajah et al., 2018b). Considering that cost implications may often be the primary deterrent in utilising a particular satellite-earth observation dataset, the emergence of freely-available and improved multi-spectral imagery, as well as geospatial cloud computing platforms has created new and exciting opportunities for large-scale LULC mapping (Hojas-Gascon et al., 2015; Immitzer et al., 2016). In this preliminary assessment, we aim to demonstrate how the power of geospatial cloud computing can be leveraged to exploit the unique characteristics of Sentinel-2 imagery to map *Cannabis sativa* within the Eastern Cape province of South Africa.

2.1.1 Methodology

Data acquisition and image processing

In this study, the Harmonized Sentinel-2 Multi-Spectral Instrument (MSI), Level-2A image collection for the study region was acquired and processed using the Google Earth Engine (GEE) geospatial cloud computing platform. GEE is a freely-available, cloud-computing platform which enables access to high-performance computing power for planetary-scale geospatial analysis (Gorelick et al., 2017). The cloud-computing power of GEE ensures that the user's personal computing power is never an issue, which is a common limiting factor when working with these larger data sets using traditional approaches (Sidhu et al., 2018). GEE provides users easy access to a multi-petabyte curated catalogue of earth observation datasets (Padarian et al., 2015; Gorelick et al., 2017; Sidhu et al., 2018). These include inter alia the entire Landsat and Sentinel (1 and 2) archives, climate forecasts, as well as socio-economic data (Gorelick et al., 2017).

According to Gorelick et al. (2017), approximately 6000 scenes per day from active missions are added to the catalogue, with only a 24-hour latency period between image acquisitions and uploads. Users may also request for new datasets to be added to the public catalogue or privately upload their own data to the platform and share these with other users if desired (Gorelick et al., 2017). In addition to the large catalogue of data, GEE provides built-in algorithms for manipulating and analysing the data, as well as a programming interface to create, customize and automate the running of algorithms (Padarian et al., 2015).

The Sentinel-2 image collection used in this study was first filtered to access only good quality images (< 10% cloud coverage) for the period 01st January 2022-28th February 2002. In total there were 20 images which met this criterion. The Sentinel-2 sensors have a revisit frequency of approximately five days and provide medium-high resolution spatial data (10 – 20 m) across 13 bands over a swath width of approximately 290 km (Ramoelo et al., 2015; Hojas-Gascon et al., 2015; Rajah et al., 2018b). Three of the thirteen bands have been strategically situated within the red-edge and short-wave infra-red region specifically for vegetation species mapping (Cho et al., 2012; Hedley et al., 2012).

Following the acquisition of the Sentinel-2 images, 17 spectral indices (Table 2-1) were generated and added to each of the images which could then be used during the classification process. The selection of vegetation indices (VIs) to be used was subjective and guided by their frequency of application and performance in the literature (Xue and Su, 2017; Bolyn et al., 2018; Yeom et al., 2019; de Castro et al., 2021; Rebelo et al., 2021). However, it should be noted that the methods implemented herein allow for additional VIs to be included or feature selection (to optimize the combination of bands and VIs) to be employed during the classification.

A single composite image was generated from the 20 images by determining the median values for each of the desired spectral bands (2, 3, 4, 5, 6, 7, 8, 8A, 11 and 12) and spectral indices. The classification of *Cannabis sativa* and other land use land cover (LULC) classes in the region was undertaken by performing a supervised classification. For this purpose, training points of known locations for the various LULC classes that are to be mapped are required so that the unique spectral characteristics of these classes can be used to train the classification algorithm (Tassi and Vizarri, 2020; Sujud et al., 2020). Training data can be easily added in GEE as either points or polygons. The training data used in this study includes ground-truth fields (polygons) of *Cannabis sativa* plantations, as well as points which were identified from visual inspection of the high-resolution reference imagery basemap available directly in GEE.

Table 2-1 List of vegetation indices used in this study

Name	Equation
Normalized Difference Vegetation Index	$\frac{NIR - Red}{NIR + Red}$
Green Normalized Difference Vegetation Index	$\frac{NIR - Green}{NIR + Green}$
Red-Edge Normalized Difference Vegetation Index	$\frac{NIR - Red_{edge1}}{NIR + Red_{edge1}}$
Enhanced Vegetation Index	$2.5 * (\frac{(NIR - Red)}{(NIR + 6 * Red - 7.5 * Blue) + 1})$
Soil Adjusted Vegetation Index	$\frac{(NIR_{narrow} - RED)}{(NIR_{narrow} + RED + 0.5) * 1.5}$
Simple Blue and Red-Edge Ratio	$\frac{BLUE}{Red_{edge1}}$
Simple NIR and Red-Edge Ratio	$\frac{NIR}{Red_{edge1}}$
Simple NIR Ratio	$\frac{NIR}{Red}$
Green Chlorophyll Index	$\frac{NIR}{Green} - 1$
Built-up Area Index	$\frac{Blue - NIR}{Blue + NIR}$
Leaf Carotenoid Content	$\frac{Red_{edge3}}{Blue - Red_{edge1}}$
Leaf Chlorophyll Content	$\frac{Red_{edge3}}{Red_{edge1}}$
Leaf Anthocynanid Content	$\frac{Red_{edge3}}{Green + Red_{edge1}}$
Modified Chlorophyll Absorption in Reflectance Index	$\left((Red_{edge1} - Red) - 0.2 * (Red_{edge1} - Green)\right) * (Red_{edge1}/Red)$
Plant Senescence Reflectance Index	$\frac{Red - Green}{Red_{edge2}}$
Plant Pigment Ratio	$\frac{Green - Blue}{Green + Blue}$
Photosynthetic Vigour Ratio	$\frac{Green - Red}{Green + Red}$

Eight broad LULC were identified, and training data was collected by identifying pixels within the image that completely contained one of these classes (Table 2-2). The selection of these pixels was guided by a priori knowledge of the study area acquired from multiple site visits and our ability to identify classes through visual interpretation.

A total of 2000 points were randomly captured for all classes, with 70% of this data being randomly selected for the training of the classification algorithm and the remaining 30% being reserved for validation of the classification accuracy (Odindi et al., 2016; Midekisa et al., 2017).

In order to model and predict the 8 broad LULC classes, some of the commonly used machine learning classification algorithms available in GEE were deployed (Orieschnig et al., 2021). A brief overview of these algorithms is provided below with more detailed explanations available in Orieschnig et al. (2021) and Sujud et al. (2021):

- Classification and Regression Tree (CART): The CART algorithm is a tree-based classifier which can be used for the classification of regression (numerical) and categorical (classification) data. This classifier attempts to find an attribute or threshold which can then be used to split the training data more effectively into subsets. This split is then used as a node in the tree with the subsets becoming branches of the tree. Each of the subsets are then subdivided further until a point is reached whereby no further splits are possible.
- Random Forest (RF): The RF algorithm is an ensemble-based classification and regression tree classifier which grows several trees instead of one to enhance the classification performance. The trees are trained in a similar manner as the CART classifier; however, several decision trees are created, and these results are then aggregated to predict the response of these decision trees with the aim of improving the accuracy of the final result.
- Gradient Tree Boosting (GTB): The GTB classifier is also an ensemble-based classification approach. However, the GTB approach differs from RF as it limits the complexity of trees by confining individual tress to a weak prediction model. An ensemble of these weak learners is then iteratively combined to create stronger ones by following a gradient descent procedure to minimize the loss function at every step.
- Support Vector Machine (SVM): The SVM classification approach aims to identify the boundary that maximizes the distance between nearest data point of all classes. These data points are used to develop support vectors which are then used as the basis for the computation of the hyperplane that serves as a boundary to separate classes and reduce the number of misclassified pixels.

The performance of each classification algorithm was then determined by comparing the overall accuracy (OA), user accuracy (UA), producer accuracy (PA) and kappa coefficient. The model which achieved the highest accuracy scores across all the performance metrics was then selected to perform the image classification using all the training data and following a pixel-based classification approach.

Table 2-2 A description of the LULC classes that were identified and categorized for mapping

Broad LULC classes	LULC present in each broad LULC class
1. Cannabis sativa	Cannabis sativa
2. Water	All open water bodies
3. Bareground	Bare soil and erosion
4. Grass	Grasslands
5. Sparse forest and woodland	Intermediate and tall trees or shrubs
6. Buildings and Infrastructure	Infrastructure, urban areas, settlements and roads
7. Agriculture	Irrigated and dryland agriculture
8. Dense forest	Dense stands of intermediate and tall trees

2.1.2 Results

Identifying the best performing classifier

Overall, the best performing classification algorithm was the GTB classifier, marginally outperforming the RF classifier. The LULC classification using the GTB model achieved an OA of 87.00%, as shown in Table 2-3. The average class-specific PA and UA for the GTB classification were 87.00% (± 9.09) and 87.00% (± 5.55), respectively. The water class was most accurately predicted within the GTB classification, whereas sparse forest and woodland were least accurately predicted. The GTB classifier was selected to perform the final image classification due to its overall performance and ability to fairly accurately identify *Cannabis sativa*. The output of the final classification performed using the GTB classification is shown in Figure 2-1.

2.1.3 Discussion and Conclusions

This study explored the utility of using the GEE geospatial cloud computing platform to process and analyse multi-spectral Sentinel-2 imagery to map LULC with a particular focus on mapping *Cannabis sativa*. In general, we found that we were able to map LULC at a relatively high accuracy, capture the spatial heterogeneity within the study region and adequately distinguish between *Cannabis sativa* and other LULC classes. Comparisons between the various classification algorithms on classification accuracy, revealed that the various machine learning algorithms available within GEE performed relatively well at mapping LULC within the study area (OA ≥ 80%).

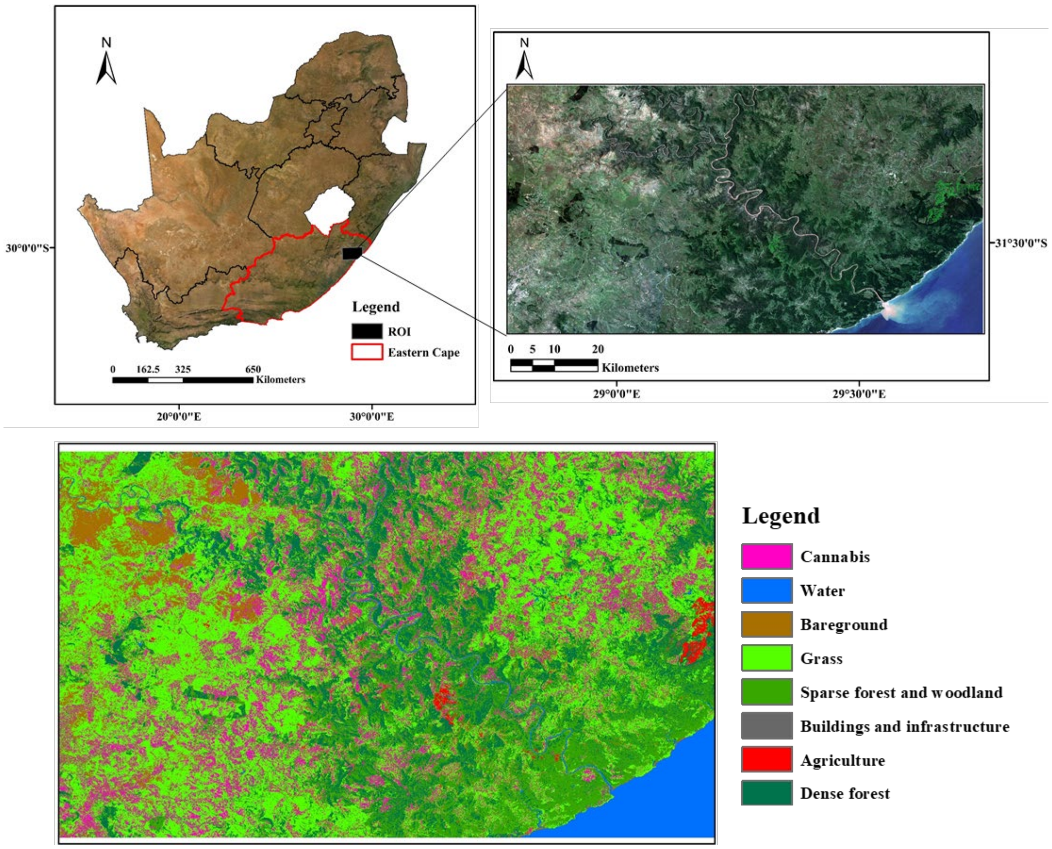


Figure 2-1 LULC classification result for the study region at a 10-meter spatial resolution, with the Sentinel-2 RGB composite shown on the top right

However, it should be noted that the training and evaluation of these algorithms were performed using a limited training dataset that was almost entirely collected from visual inspection of the high-resolution reference imagery basemap and Sentinel-2 True colour image. The collection of training data from visual inspection promoted the ease of application and expedited the classification process during the formative stages of this study. However, it should be noted that this may contribute to occurrences of misclassification. Some of the data points may be incorrectly identified or may not adequately represent the unique spectral properties for each of the classes that are to be mapped. Subsequently, it is recommended that future classifications which are centred around refining the methodology adopted herein, incorporate training data that consists of a more extensive list of ground truth data where possible. This may then allow for a more accurate and objective assessment of the performance of the various classification algorithms to be ascertained (Midekisa et al., 2017).

Table 2-3 Classification accuracies for the various classification algorithms available in GEE

	Accuracy Assessment							
	CART		**SVM**		**RF**		**GTB**	
Overall Accuracy (%)	81.00		70.00		88.00		87.00	
Kappa Coefficient	78.00		0.66		0.86		0.85	
	PA (%)	UA (%)	PA (%)	UA (%)	PA (%)	UA (%)	PA (%)	UA (%)
Cannabis	74.00	71.00	65.00	53.00	88.00	83.00	88.00	88.00
Water	91.00	95.00	96.00	92.00	98.00	91.00	100.00	92.00
Bareground	86.00	83.00	81.00	84.00	84.00	95.00	86.00	89.00
Grass	73.00	74.00	52.00	56.00	86.00	85.00	82.00	83.00
Sparse forest and woodland	64.00	65.00	46.00	42.00	64.00	78.00	70.00	76.00
Buildings and Infrastructure	76.00	82.00	57.00	66.00	90.00	85.00	84.00	89.00
Agriculture	94.00	92.00	92.00	95.00	96.00	87.00	96.00	93.00
Dense forest	84.00	84.00	68.00	69.00	91.00	84.00	89.00	84.00

The classification accuracy of each LULC class ranged between 70-100% for the GTB classification. The major source of inaccuracy in this classification was generally due to the misclassification of *Cannabis sativa*. The confusion in this instance was largely unidirectional. This confusion may be a combined consequence of the training data that was used during the classification process and the limited number of spectral features used during the classification process which may have contributed to difficulties in distinguishing between certain features which are spectrally similar (Böhler et al., 2018; Zhao et al., 2019).

The use of additional VIs and inclusion of surface textural features may allow for the unique spectral and physical characteristics of the various LULC classes to be more adequately represented and should be explored further during the refinement of the method described herein. Furthermore, object-oriented image methods are becoming increasingly popular to perform classifications on higher resolution imagery due to their ability to generally produce improved results in comparison to traditional image analysis pixel-based classification approaches (Tassi and Vizarri, 2020). Therefore, this is another option that should be explored further to potentially improve on the current classification.

While the preliminary results of the classification process are satisfactory, the aforementioned options may allow for further improvements to be made. Nevertheless, the results of these preliminary investigations have demonstrated that through the development of a robust methodology that can be relatively easily replicated as it utilizes freely-available multi-spectral imagery and GEE, there exists immense potential to map the location, distribution and extent of *Cannabis sativa* in other potential areas of interest.

2.2 *Cannabis sativa* land suitability mapping for dryland production

Two methods were used to evaluate land suitability for dryland production of *Cannabis* using available datasets.

2.2.1 Mapping using ArcGIS Predictive Analysis Tool

The Predictive Analysis Tool (PAT) is available as an add-in ArcGIS (ESRI, 2014). The methodology assumes that the environmental / bioclimatic conditions of the known locations can be generalised to predict other locations that match those conditions. There are few publications associated with the use of this tool to identify locations where prehistoric humans frequented (Caracausi et al., 2018), and distribution range for Zika virus carried by Aedes mosquito (Attaway et al., 2017). Caracausi et al. (2018) noted for the case of archaeological predictions, the biases in the selection of known locations might affect the outcome.

For the current study, we utilised 28 data layers derived from the Schulze (2007) database, including constraints of rainfall, temperature, aridity index, slope (<12%), and using the *Cannabis sativa* presence data as constraint for PAT modelling.

Rainfall

As noted by literature quoted above, rainfall and water availability are important criteria that limit the areas where *Cannabis sativa* can be grown. The project is focusing on identifying areas where rainfed agriculture can be conducted. We considered not only total annual rainfall but also rainfall for the growth months of September to April (Figure 2-2 and Figure 2-3; Lynch & Schulze, 2007; Schulze & Lynch, 2007) when temperatures are warm enough and do not experience frost, is essential.

Temperature

Temperatures during the growing period are recommended to be between 24˚C and 27˚C for subtropics, in addition to areas being frost-free. Considering that with climate change, high temperature extremes might negatively impact the crop, thus, we included extremes in maximum temperature recorded for the period of 1950 to 2000 (Figure 2-4; Schulze & Maharaj, 2007). We also included mean and minimum monthly daily temperatures for the growth months of September to April (Schulze & Maharaj, 2007), e.g. Figure 2-5 which shows minimum daily temperature for September.

Aridity Index

Areas with high heat (or high potential evapotranspiration) present high risk to the plants and therefore are not ideal for growing *Cannabis sativa*. The SA Atlas provides means of reference crop evaporation in mm that are FAO Penman-Monteith Equivalent (Schulze et al., 2007). Thus, monthly aridity index was calculated as a ratio of monthly potential evapotranspiration (PET) and median monthly rainfall (Schulze and Lynch 2007) for the growing period (8 months September to April). To avoid division by zero (since there were areas with zero rainfall), a value of 0.1 was added to the median monthly rainfall (using Raster Calculator) before calculating the index. The result for the month of September is shown in Figure 2-6 as an example of the variation across South Africa.

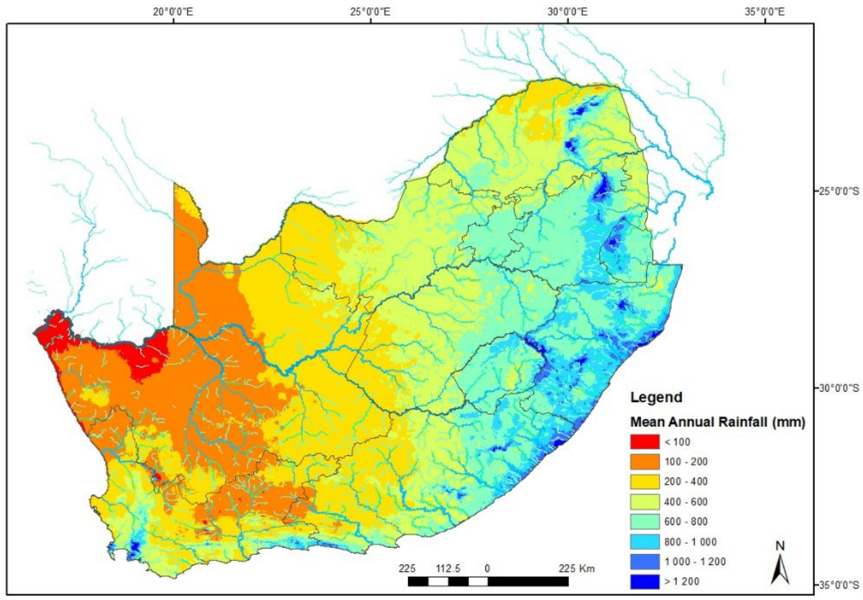


Figure 2-2 Mean annual precipitation (mm) derived from Schulze (2007) database

Slope

Areas with slope >12% are considered unsuitable for growing *Cannabis sativa* and these areas are highlighted in red in Figure 2-7.

Cannabis sativa presence data as constraint for PAT

There is limited data on where *Cannabis sativa* is being grown by local communities in South Africa. A set of successful communities were investigated by Ida Højgaard (2021) in her thesis into *Cannabis sativa* production by rural communities in Eastern Cape in South Africa. Her study was conducted in two inland and two coastal communities in Mpondoland. Figure 2-8 shows the general area where the communities are located. The climatic range of these locations (in terms of rainfall, temperature, aridity index layers, in addition to slope of <12%, were used as habitat limitation for the PAT modelling.

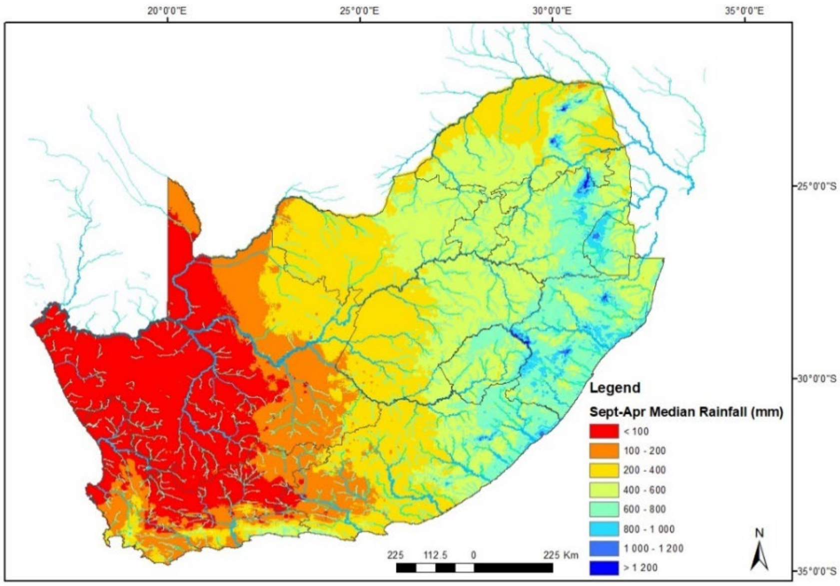


Figure 2-3 Total rainfall for the growing period months of September to April derived from Schulze (2007) database.

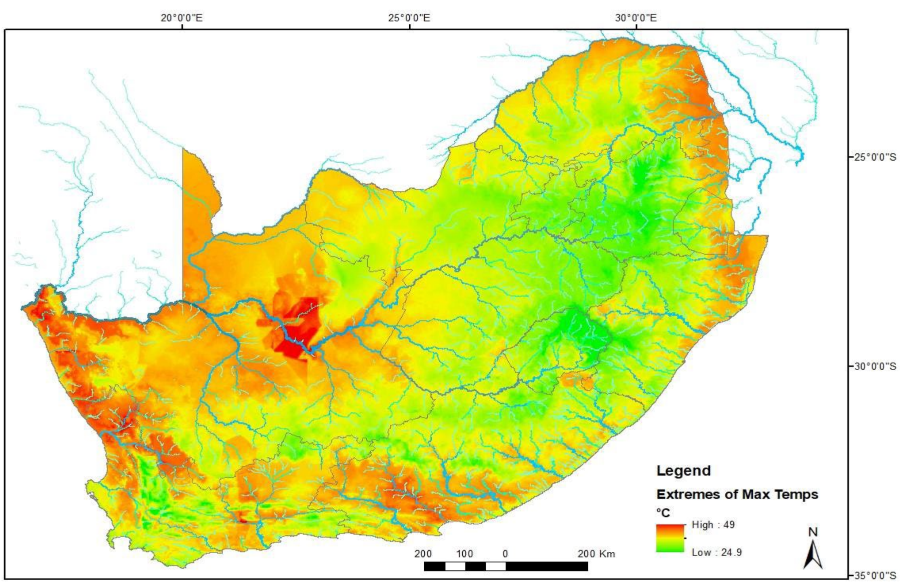


Figure 2-4 Extremes (1950 - 2000) of maximum temperature (°C) for all 12 months derived from Schulze (2007) database

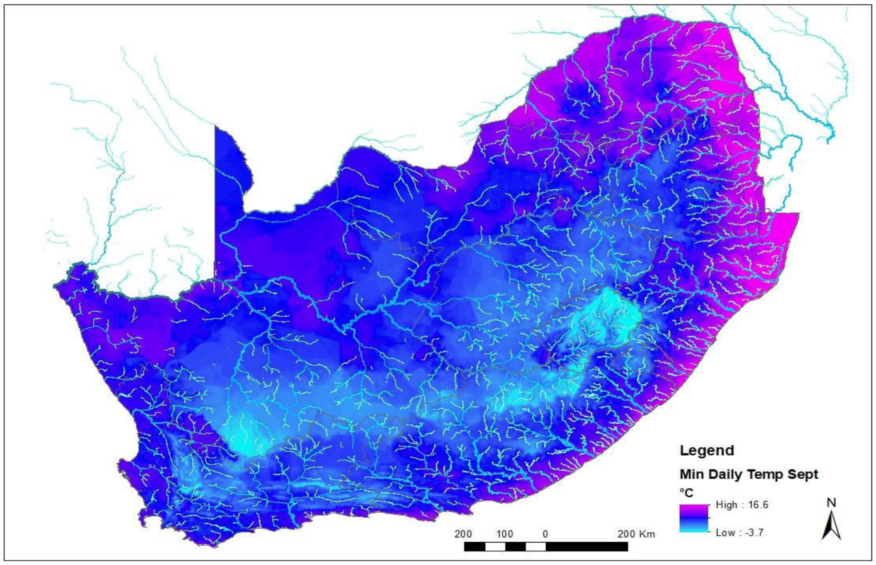


Figure 2-5 Minimum daily temperature (°C) for September derived from Schulze (2007) database

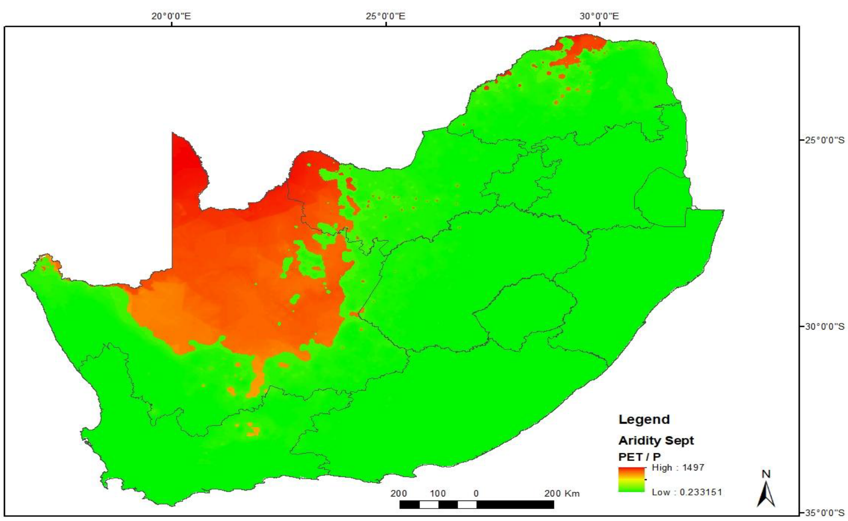


Figure 2-6 Monthly Aridity Index developed from a ratio of potential evapotranspiration (PET) to rainfall (P) for September using data derived from Schulze (2007) database

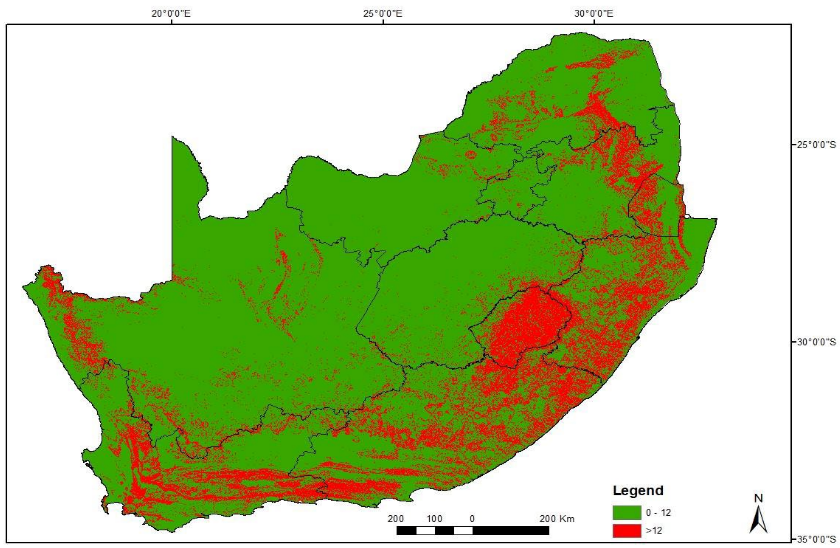


Figure 2-7 Percent slope calculated from Shuttle Radar Topography Mission (SRTM) 90 m Digital Elevation Model

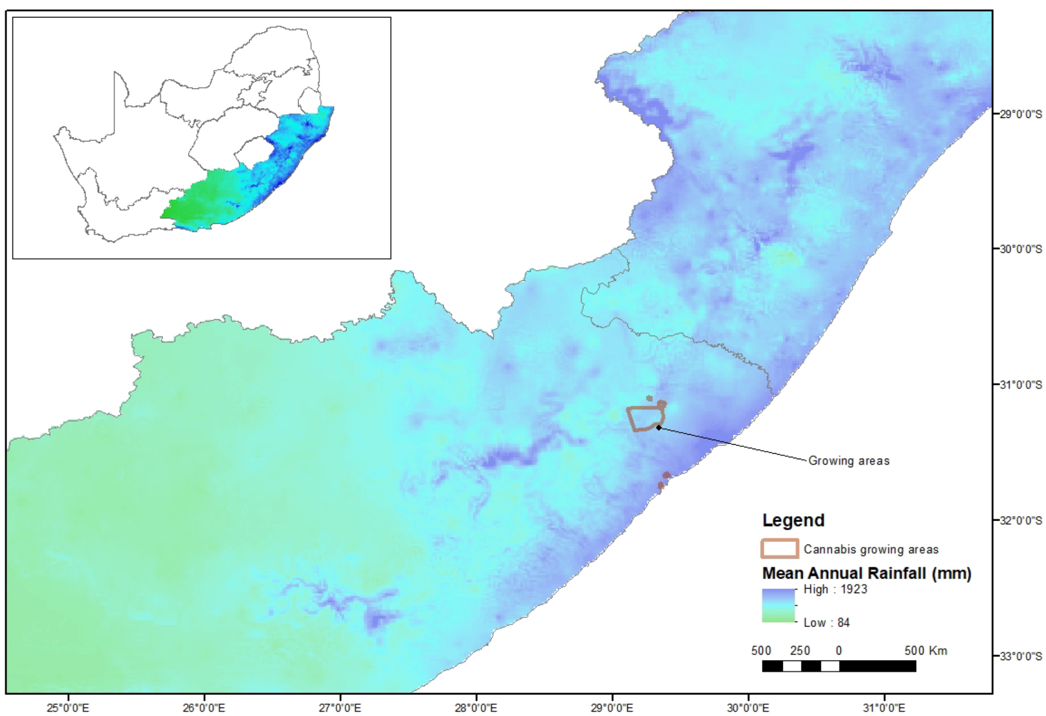


Figure 2-8 Known general location where Cannabis sativa *is being grown by rural communities*

2.2.2 Mapping through the implementation of species distribution modelling methods in Google Earth Engine

The identification of suitable growing areas for *Cannabis* was determined in this study by implementing species distribution modelling based on the GEE workflow described in Crego et al.

(2022). Ecological niche or species distribution modelling (SDM) are dependent on good quality data being available for analyses (Araújo et al., 2019; Leroy et al., 2018; Sillero et al., 2021). The first step in the modelling process is to acquire data on known species locations. While the acquisition of presence and absence data is recommended for SDM analysis it is often the case that presence-only data is available. In this study we acquired *Cannabis* presence-only data from i) site visits, ii) using indigenous knowledge to guide the analysis of high-resolution basemap imagery available directly in GEE and iii) a landcover map developed for the study area. In total 908 presence-only records were used for the SDM analysis. The dataset was then filtered by applying a function so that only one occurrence record per pixel at the chosen spatial resolution for the analysis (1000 m) exists.

There are a number of predictor variables available in GEE which can be used for SDM analyses. We selected a combination of climate (annual mean temperature, temperature seasonality, maximum temperature of the warmest month, minimum temperature of the coldest month and annual precipitation; Hijmans et al., 2005), elevation (Farr et al., 2007) and soils (texture and pH; Hengl et al., 2021) variables as covariates to be used in the model.

All predictor variables were combined into a single multi-band image which was then filtered to exclude locations in steep terrain (slope > 12%; Farr et al., 2007) and where waterbodies were present (using the global surface water product; Pekel et al., 2016). A spatial block cross validation technique (repeated 10 times) was implemented to randomly partition spatial blocks (200 x 200 km) for model training (70%) and validation (30%), with pseudo-absences being randomly generated during each iteration. During this process presence-only data and pseudo-absences were balanced within the training and validation datasets (Crego et al., 2022).

Several non-parametric classifiers are available within GEE which can be used for SDM applications. These include random forest (RF), support vector machine (SVM), classification and regression trees (CART), gradient tree boosting (GTB) and maximum entropy (MAXENT). In this study, training data was fitted with the RF classifier to perform a probabilistic classification which was then used to distinguish the various suitability classes. Since we only possessed presence data, pseudo-absence data needed to be generated in order to fit the models used for the SDM analysis (Phillips et al., 2009). For this purpose, a two-step environmental profiling approach was implemented to restrict the area in which pseudo-absences could be generated. Random pseudo-absences were created using k-means clustering based on Euclidean distances to create two data clusters, one which possessed similar environmental characteristics to presence locations (200 random points) and the other which was dissimilar to the presence data. The pseudo-absence data was then derived within the boundaries of the data cluster that was dissimilar to the presence data.

The accuracy of the model was then assessed by comparing the simulated output for the 10-model iterations against the data that was reserved for validation during each iteration. Once the model had demonstrated satisfactory performance across all key performance metrics it could then be used to map suitable growing areas for *Cannabis* at a larger spatial scale. For this purpose, the aforementioned predictor variables were acquired within GEE for the entire country and the model was then applied to map suitable growing areas for *Cannabis* within South Africa.

2.3 Results and Discussion

The project identified more grow sites for *C. sativa* under rainfed/dryland conditions. Due to the illicit nature of all historical cultivation in South Africa, and the threat of crop destruction if the grow sites were found by law enforcement agencies, much of the cultivation is undertaken in sites that are very difficult to access e.g. along riverbanks in deeply incised river valleys. These sites have very limited or no access to irrigation. However, moderate-high resolution earth observation data enabled us to identify grow sites in optimum habitat where there was no option of irrigation, and where small-scale growers had sustained production. It is clear from the success of indoor cultivation of *C. sativa* that regular (daily in most cases) watering is essential for plant survival, but the concern of this study is to identify those areas where dryland cropping is possible without access to irrigation, and this has required a modelling approach that uses the successful dryland growers of the Umzimvubu river valley as presence-only input. In dryland/rainfed cultivation of a temperate herbaceous plant such as *C. sativa*, rapid changes in environmental variables such as maximum temperature, relative humidity, soils moisture status and wind speed (which effect vapour pressure deficit) can rapidly place a crop under extreme and terminal stress. Previous trials of *C. sativa* under dryland conditions in the Eastern Cape have failed when extreme events (e.g. Berg wind conditions) resulted in very high vapour pressure deficit during the months of November and December and the entire crop was lost. This report is therefore designed to identify those areas where dryland production, without access to irrigation water, is low risk. The results presented in this report therefore focus exclusively on the sustainable production of *C. sativa* under dryland/rainfed conditions. These results by no means reflect the conditions under which this species can be grown when there is access to irrigation water, or in a controlled environment in tunnels.

2.3.1 Results of Predictive Analysis Tool (PAT) mapping

The results of the Predictive Analysis Tool indicate areas located in Eastern Cape and KwaZulu Natal to be suitable (Figure 2-9). These areas have slope of <12% and match the range of rainfall, temperature, aridity index characteristics of the *C. sativa* presence data. Notably the predicted areas are very limited but this is due to the constraint of the limited presence data.

In South Africa, this tool was used by an MSc student at the Institute for Water Research for evaluating grassland areas where free-ranging livestock prefer to graze (Mkabile, 2019). This research was aimed at addressing issues of rangeland degradation in two catchments in the Eastern Cape. The tool focused on answering two research questions: (1) where do livestock spend time in the wet and dry seasons?; (2) how can areas of potential livestock distribution be identified in other catchments where actual distribution is unknown? Mkabile's research included tracking livestock during the wet and dry seasons using GPS collars to obtain ground data for the model. These distribution data were combined with selected physical landscape variables to identify selectivity of the rangeland areas. The GPS location data in addition to the physical landscape variables were used to predict potential livestock distribution in quaternary catchments T12A (Mgwalana rural area) and T35A-E (Tsitsa River catchment). The key findings of her research were that livestock preferred accessible areas with gentle terrain near water sources, avoiding south-facing slopes (which are cooler due to less solar radiation received). Also, the livestock were attracted to vegetation in the riverine riparian zones.

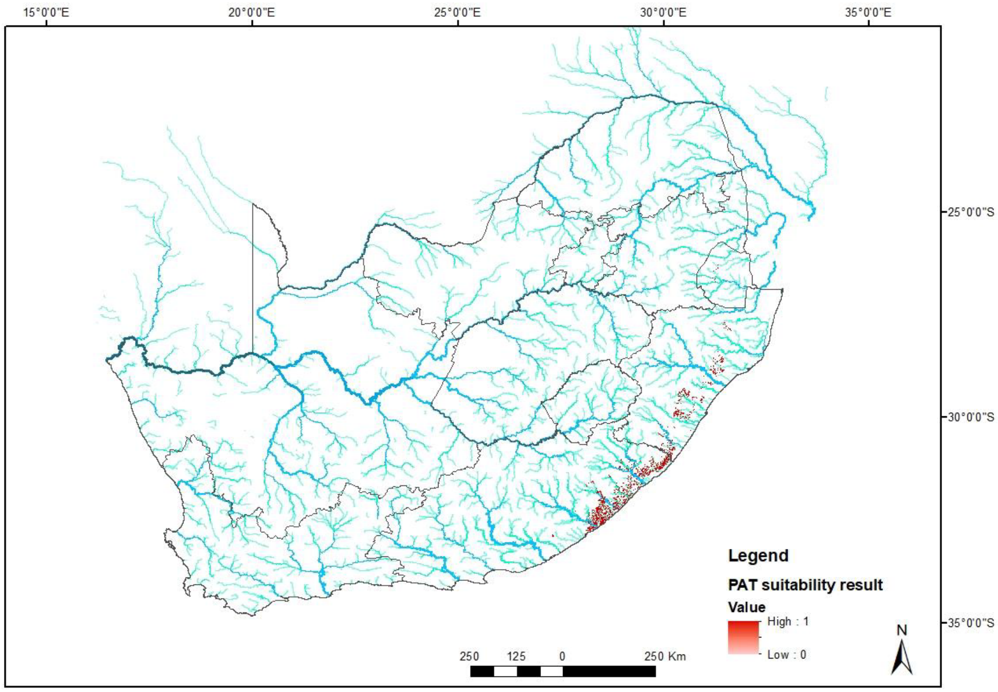


Figure 2-9 Distribution of predicted suitable growing areas for C. sativa across South Africa using Predictive Analysis Tool

2.3.2 Results of Species Distribution Modelling (SDM) mapping

The model accuracy was assessed by determining the Area Under the Curve of the Receiver Operator Characteristic (AUC-ROC), Area Under the Precision-Recall Curve (AUC-PR), sensitivity and specificity for the validation data during each of the 10 iterations. The predicted suitable growing areas within the region of interest used during training and validation of the SDM (Figure 2-10) was then determined as the average of the simulated presence probability across all iterations. The mean AUC-ROC and AUC-PR for the 10 iterations (Table 2-4) were 0.85 (±0.03) and 0.86 (±0.05), respectively and indicated good model performance. The range of values of the predictor variables for the highly suitable growing areas are consistent with those values identified during the literature review (Table 2-5). The suitable growing areas for *Cannabis* across SA (Figure 2-11) was then determined by applying the trained SDM model.

Table 2-4 *A summary of the accuracy assessment results for the RF model to predict suitable growing areas for Cannabis within the region of interest (ROI) used during the SDM training and evaluation*

Model Run	AUCROC	AUCPR
1	0.81	0.92
2	0.80	0.88
3	0.90	0.86
4	0.87	0.90
5	0.85	0.86
6	0.82	0.81
7	0.86	0.92
8	0.88	0.86
9	0.84	0.77
10	0.88	0.83

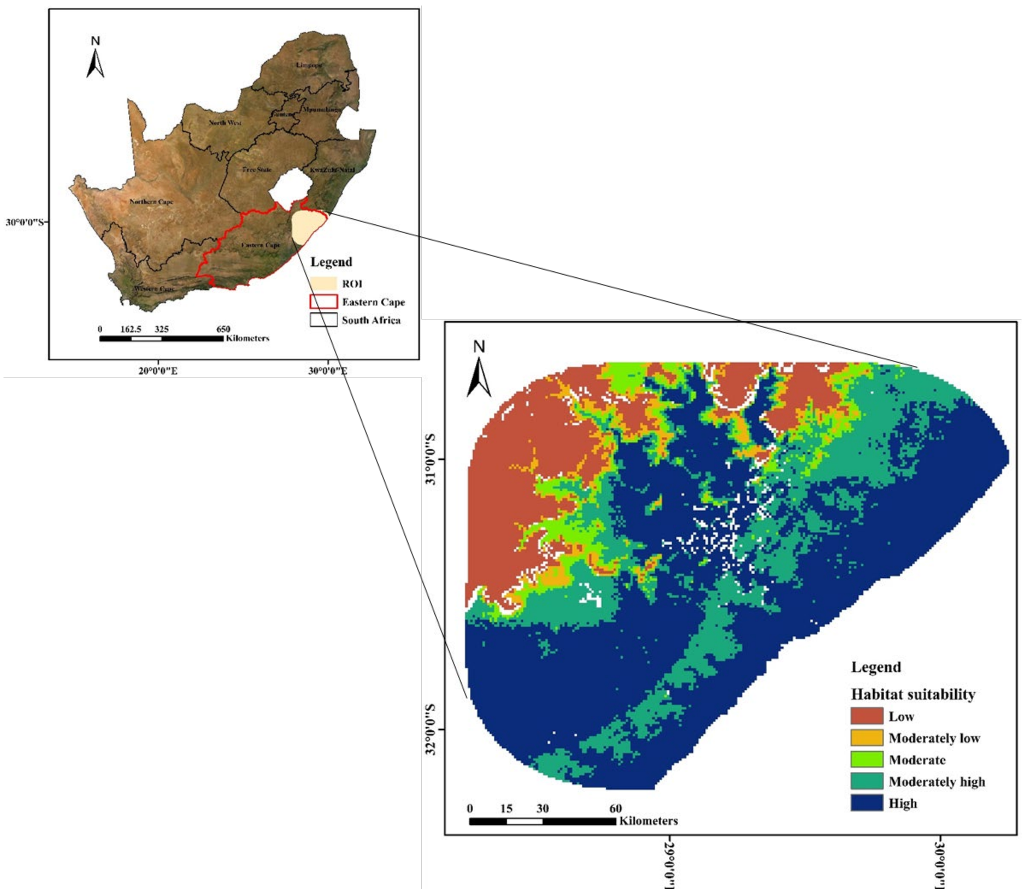


Figure 2-10 Predicted suitable growing areas for Cannabis within the region of interest (ROI) used during the SDM training and evaluation

Table 2-5 Average predictor variable value ranges across each suitability class within the region of interest used during the SDM training and evaluation

Variable	**Low**	**Moderately Low**	**Moderate**	**Moderately High**	**High**
Mean Annual Temp (˚C)	14.84	15.94	16.22	16.88	17.43
Temp Seasonality (˚C)	35.20	31.85	31.75	29.02	26.02
Max Temp of Warmest Month (˚C)	25.19	25.63	25.86	25.76	25.50
Min Temp of Coldest Month (˚C)	1.51	3.32	3.56	5.10	6.98
MAP (mm)	807.80	807.60	802.30	842.00	899.30
Elevation (m)	1383.01	1136.60	1058.30	783.60	582.30
USDA Texture (0-20 cm)	Silty Clay Loam	Silty Clay Loam	Loam	Loam	Loam
USDA Texture (20-50 cm)	Silty Clay Loam	Silty Clay Loam	Loam	Loam	Loam
pH (0-20 cm)	5.80	5.86	6.04	6.01	6.07
pH (20-50 cm)	5.80	5.86	6.05	6.03	6.07

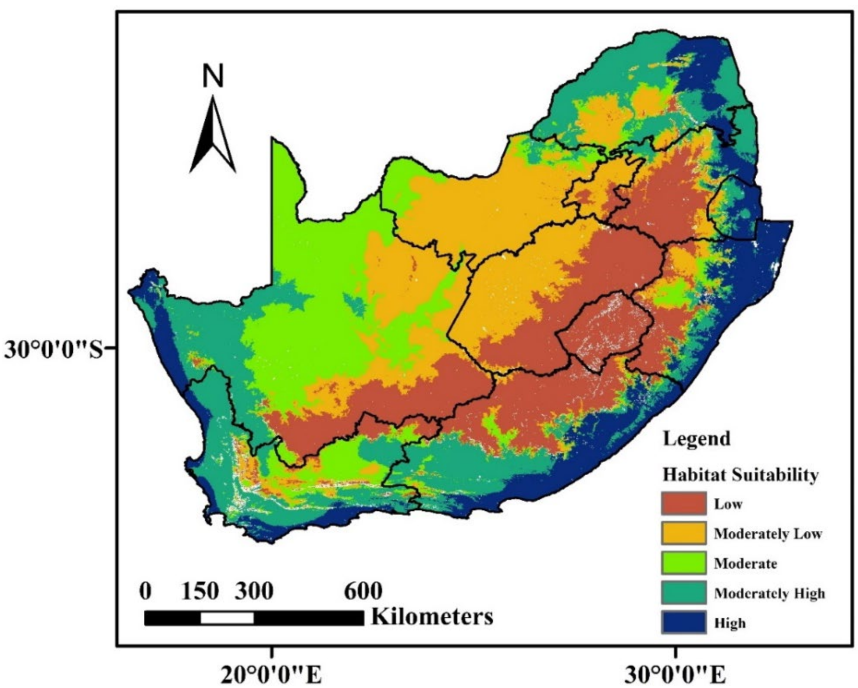


Figure 2-11 Distribution of predicted suitable growing areas for Cannabis across South Africa

The rise in the availability of freely available and spatially explicit datasets has contributed to an increase in the use of these datasets and development of SDMs to better understand patterns of occurrence across space and time or predict habitat suitability (Guisan et al., 2017; Kass et al., 2018; Crego et al., 2022). However, the often-complex spatial analyses which form the basis of SDM can prove to be a barrier to those that lack the computational resources and technical skills required to successfully implement these models (Gorelick et al., 2017; Crego et al., 2022).

Considering these limitations, the GEE workflow developed by Crego et al. (2022) can prove to be an invaluable resource for SDM analyses. The workflow adopts many of the standard SDM practices used for predicting habitat suitability and assessing model performance whilst also leveraging the computational power of GEE and providing the user with access to a multi-petabyte curated catalogue of freely available data housed on the platform.

Furthermore, the workflow is relatively easy to follow, requires minimal adaptation or modification and is accompanied by detailed tutorials to assist the user with navigating and performing various SDM related tasks within the GEE environment. Despite the many advantages associated with the implementation of SDM in the GEE environment, Crego et al. (2022) states that the user quotas which are imposed to prevent the computing capacity of the entire user community being negatively impacted, may result in resource-intensive tasks triggering memory-limits, subsequently preventing results being rapidly displayed on-the-fly within GEE's interactive user interface (Gorelick et al., 2017; Navarro, 2017).

While this issue can be circumvented by executing tasks in a batch mode whereby the results of the analyses are exported to Google Drive or Google Cloud Storage, the time taken for this is highly dependent on the volume of data being exported as well as the internet speed and connectivity (Navarro, 2017). Additionally, Google provides limited free storage capacity (15 Gb) which is shared among all of its apps therefore users may be further restricted by the amount of data they are able to export and store (Navarro, 2017). While the aforementioned limitations are relatively minor and specific to GEE, often the biggest challenge to developing representative and accurate SDMs is the availability of sufficient good quality occurrence data (presence and absence locations) at the scale of application.

Since such data are generally not readily available or easily attainable, occurrence data used during training and validation of the SDMs is biased by sampling efforts that are restricted to regions whereby the data is most easily accessible (De Simone et al., 2021; Crego et al., 2022). This limitation in particular has a significant bearing upon the accuracy and representativity of the results presented in this study. Due to the remote locality of many dryland growing areas as well as past and present legislation which have contributed to negative perceptions surrounding *Cannabis* cultivation (Kitchen et al., 2022), the acquisition of sufficient good quality occurrence data at a national scale is extremely challenging.

Subsequently, sampling efforts in this study were limited to a relatively small region for which data was available. While the model was shown to perform well when applied at the scale for which the occurrence data was acquired (Figure 2-10) there remains some uncertainty regarding the i) the accuracy of occurrence data used to train and validate the model and ii) accuracy of the final model when applied at a national level (Figure 2-11).

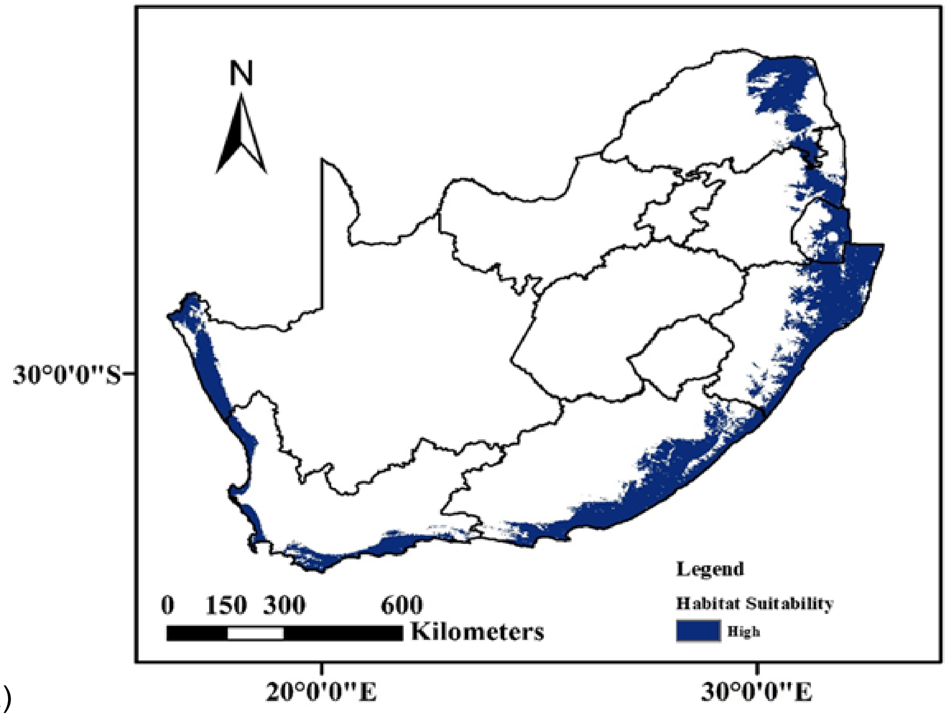
As Crego et al. (2022) note, poor predictive performance because of biased or unreliable occurrence data can't be remedied by the improved computational power or access to data that GEE provides. Therefore, caution should be exercised if using the results presented in this study to guide and inform decision-making. Notwithstanding this limitation, we found the GEE SDM workflow to be quite promising particularly as users of all experience levels can leverage the immense potential of GEE with minimal effort to rapidly produce high-quality maps of habitat suitability, with the added ability to easily share the methods and results which makes these analyses more transparent and reproducible. While future developments within the GEE environment can be integrated and used to improve the flexibility and functionality of the SDM workflow, in its present form it is a powerful tool to aid environmental practitioners or researchers in better-understanding species distributions across space and time or in predicting habitat suitability.

2.3.3 Comparison of the two modelling results

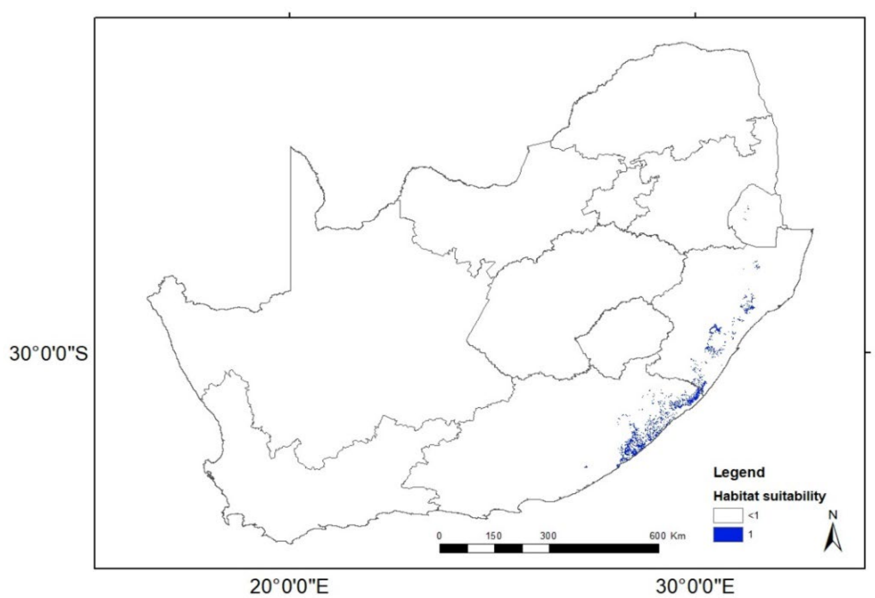
The results from the two approaches used in this modelling study demonstrate that there is limited opportunity in the region for expanding dryland grow sites beyond the Umzimvubu River valley. Although the Suitability Distribution Model suggests a somewhat wider growth area relative to the PAT result (Figure 2-12), the risks associated with climatic extremes in this wider region during the growing season far outweigh the benefits. Without access to irrigation water to provide emergency irrigation under extreme weather events, the planting of high value cultivars (e.g. Exodus cheese) under dryland conditions will fail regularly and expose legacy farmers to debt.

There are several reports and publications that highlight the significant contribution that rainfed *Cannabis* production can make to livelihoods in the river valleys of KwaZulu Natal and the former Transkei (Højgaard, 2021; Kepe, 2007; Manu et al., 2021). Højgaard (2021)'s thesis into *Cannabis sativa* production provides a useful insight into the significant financial support that *Cannabis* can provide for rural communities in Mpondoland in South Africa. However, there are several important factors that need to be considered before embarking on recommendations for scaling up the planting operations in the region. Stone (2022) has reported most of these legacy farmers in the former Transkei "*cultivate only cannabis as their cash crop, exercising their indigenous and customary law rights. Their survival depends on cannabis as much as the preservation of these ancient cultivars depends on them."* Stone continues in his opinion article "*So, it's not a question of "licensing" an individual cannabis farmer to cultivate cannabis lawfully, but rather, what will it take to create and enable an inclusive rural economy and cannabis value-chain accessible to each household already participating in the (illicit) cannabis economy?*". This view is further supported by the work of both Kepe (2007) and Manu et al (2021). In addition, the cultivars used in this region are regarded as highly adapted to the prevailing climatic conditions. The results of the modelling of the climate envelope have confirmed that the growing conditions in this region are unique, and with associated local cultivar adaptation having taken place over centuries, Stone's argument for protecting the rights of these legacy farmers is compelling.

However, with access to irrigation at a rate of approximately 4 L plant^{-1} day^{-1}, there is a much larger region with the potential to grow the crop. This area is represented by the 'moderately high' and 'high' categories of the SDM model as shown in Figure 2-11.



(a)



(b)

Figure 2-12 Comparison of distribution of predicted highly suitable growing areas for Cannabis sativa across South Africa using (a) Suitability Distribution Mapping and (b) Predictive Analysis Tool

2.4 References

ARAÚJO MB, ANDERSON RP, BARBOSA AM, BEALE C, DORMANN CF, EARLY R, GARCIA RA, GUISAN A, MAIORAN L, NAIMI B, O'HARA RB, ZIMMERMANN NE and RAHBEK C (2019) Standards for distribution models in biodiversity assessments. Science Advances **5**(1): 1–12.

BÖHLER JE, SCHAEPMAN ME and KNEUBÜHLER M (2018) Crop Classification in a Heterogeneous Arable Landscape Using Uncalibrated UAV Data. Remote Sensing **10** (8).

BOLYN C, MICHEZ A, GAUCHER P, LEJEUNE P and BONNET S (2018) Forest mapping and species composition using supervised per pixel classification of Sentinel-2 imagery. Biotechnology, Agronomy, Society and Environment **22** 172-187.

CARACAUSI S, BERRUTI GLF, DAFFARA S, BERTÈ D and RUBAT BOREL F (2018) Use of a GIS predictive model for the identification of high altitude prehistoric human frequentations. Results of the Sessera valley project (Piedmont, Italy). Quaternary International Elsevier, 490 (September) 10–20. https://doi.org/10.1016/j.quaint.2018.05.038.

CHO MA, MATHIEU R, ASNER GP, NAIDOO L, VAN AARDT J, RAMOELO A, DEBBA P, WESSELS K, MAIN R, SMIT IPJ and ERASMUS B (2012) Mapping tree species composition in South African savannas using an integrated airborne spectral and LiDAR system. Remote Sensing of Environment **125** 214–226.

CREGO RD, STABACH JA and CONETTE G (2022) Implementation of species distribution models in Google Earth Engine. Diversity and Distributions **28**.

DE CASTRO AI, SHI Y, MAJA JM and PEÑA JM (2021) UAVs for Vegetation Monitoring: Overview and Recent Scientific Contributions. Remote Sensing **13**.

DE SIMONE W, ALLEGREZZA M, FRATTAROLI AR, MONTECHIARRI TESEI G, ZUCCARELLO V and DE MUSCHIANO M (2021) Remote Sensing **13**.

ESRI (2014) Getting Started with the ArcGIS Predictive Analysis 45.

FARR TG, ROSEN PA, CARO E, CRIPPEN R, DUREN R, HENSLEY S, KOBRICK M, PALLER M, RODRIGUEZ E, ROTH L, SEAL D, SHAFFER S, SHIMADA J, UMLAND J, WERNER M, OSKIN M, BURBANK D and ALSDORF DE (2007) The shuttle radar topography mission: Reviews of Geophysics **45**(2).

FERREIRA A, FELIPUSSI SC, PIRES R, AVILA S, SANTOS G, LAMBERT J, HUANG, J and HØJGAARD I (2021) Illicit *Cannabis* Production and Rural Livelihoods in Mpondoland, South Africa. University of Copenhagen.

GORELICK N, HANCHER M, DIXON M, ILYUSCHENKO S, THAU D and MOORE R (2017) Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sensing of Environment **202** 18–27.

GORELICK N, HANCHER M, DIXON M, ILYUSHCHENKO S, THAU D and MOORE R (2017) Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sensing of Environment **202** 18–27.

GUISAN A, THUILLER W and ZIMMERMANN N (2017) Habitat suitability and distribution models: With applications in R. Cambridge University Press.

HEDLEY J, ROELFSEMA C, KOETZ B and PHINN S (2012) Capability of the Sentinel 2 mission for tropical coral reef mapping and coral bleaching detection. Remote Sensing of Environment **120** 145–155.

HENGL T, MILLER MAE, KRIŽAN J, SHEPERD KD, SILA A, KILIBARDA M, ANTONIJEVIĆ O, GLUŠICA L, DOBERMANN A, HAEFELE SM, MCGRATH SP, ACQUAH GE, COLLINSON J, PARENTE L, SHEYKHMOUSA M, SAITO K, JOHNSON J, CHAMBERLIN J, SILATSA FBT, YEMEFACK M, WEDNT J, MACMILLAN RA, WHEELER I and CROUCH J (2021) African soil properties and nutrients mapped at 30 m spatial resolution using two-scale ensemble machine learning. Scientific Reports **11**.

HIJMANS RJ, CAMERON SE, PARRA JL, JONES PG, and JARVIS A (2005) Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology **25** 1965-1978.

HOJAS-GASCON L, BELWARD A, EVA H, CECCHERINI G, HAGOLLE O, GARCIA J and CERUTTI P (2015) Potential improvement for forest cover and forest degradation mapping with the forthcoming Sentinel-2 program. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences.

HØJGAARD I (2021) Illicit *Cannabis* Production and Rural Livelihoods in Mpondoland, South Africa. Masters Thesis, University of Copenhagen.

IMMITZER M, VUOLO F and ATZBERGER C (2016) First experience with Sentinel-2 data for crop and tree species classifications in central Europe. Remote Sensing **8**.

KASS JM, VILELA B, AIELLO-LAMMENS ME, MUSCARELLA R, MEROW C and ANDERSON RP (2018) Wallace: A flexible platform for reproducible modeling of species niches and distributions built for community expansion. Methods in Ecology and Evolution **9**(4) 1151–1156.

KEPE T (2007) Medicinal plants and rural livelihoods in Pondoland, South Africa: Towards an understanding of resource value. International Journal of Biodiversity Science and Management **3**(3) 170–183. https://doi.org/10.1080/17451590709618171.

KITCHEN C, KABBA JA, SSEKEMATTE TONNY, NELSON E, ADU-GYAMFI S, MAMETJA M, YANG C, CHANG J and FANG Y (2022) Perceptions of *Cannabis* in sub-Saharan Africa: Findings from a general population survey in six African countries with different *Cannabis* policies. Research Square Preprints.

LEROY B, DELSOL R, HUGUENY B, MEYNARD CN, BARHOUMI C, BARBET-MASSIN M and BELLARD C (2018) Without quality presence–absence data, discrimination metrics such as TSS can be misleading measures of model performance. Journal of Biogeography **45**(9) 1994–2002.

MANU E, DOUGLAS M, NTSABA MJ and TARKANG EE (2021) Perspectives of illicit marijuana growers and traders on commercial legalisation of marijuana in South Africa: considerations for policy formulation. Substance Abuse Treatment, Prevention, and Policy Substance Abuse Treatment, Prevention, and Policy **16**(1) 54–66. https://doi.org/10.1186/s13011-021-00391-w.

MIDEKISA A, HOLL F, SAVORY DJ, ANDRADE-PACHECO R, GETHING PW, BENNETT A and STURROCK HJW (2017) Mapping land cover change over continental Africa using Landsat and Google Earth Engine cloud computing. PLoS ONE **12**(9).

MKABILE QB (2019) Mapping and Predicting Potential Distribution Patterns of Free-Range Livestock in the Rural Communal Rangelands of Mgwalana, Eastern Cape, South Africa. Unpublished Thesis, Rhodes University, South Africa.

NAVARRO JA (2017) First experiences with google earth engine. Proceedings of the 3rd International Conference on Geographical Information Systems Theory, Applications and Management 250–255.

ODINDI J, MUTANGA O, ROUGET M and HLANGUZA N (2016) Mapping alien and indigenous vegetation in the KwaZulu-Natal Sandstone Sourveld using remotely sensed data. Bothalia **46**(2).

ORIESCHNIG CA, BELAUD G, VENOT JP, MASSUEL S and OGILVIE A (2021) Input imagery, classifiers, and cloud computing: Insights from multi-temporal LULC mapping in the Cambodian Mekong Delta. European Journal of Remote Sensing **54**(1) 398-416.

PADARIAN J, MINASNY B and MCBRATNEY AB (2015) Using Google's cloud-based platform for digital soil mapping. Computers & Geosciences **83** 80–88.

PEERBHAY KY, MUTANGA O and ISMAIL R (2013) Commercial tree species discrimination using airborne AISA eagle hyperspectral imagery and partial least squares discriminant analysis (PLS-DA) in Kwazulu–Natal, South Africa. ISPRS Journal of Photogrammetry and Remote Sensing **79** 19–28.

PEERBHAY KY, MUTANGA O and ISMAIL, R (2014) Investigating the capability of few strategically placed worldview-2 multispectral bands to discriminate forest species in Kwazulu-Natal, South Africa. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing **7**(1) 307–316.

PEKEL J, COTTAM A, GORELICK N, BELWARD and AS (2016) High-resolution mapping of global surface water and its long-term changes. Nature **540** 418-422.

PHILLIPS SJ, DUDÍK M, ELITH J, GRAHAM CH, LEHMANN A, LEATHWICK J and FERRIER S (2009) Sample selection bias and presence-only distribution models: Implications for background and pseudo-absence data. Ecological Applications **19**(1) 181–197.

RAJAH P, ODINDI J and MUTANGA O (2018b) Evaluating the potential of freely available multispectral remotely sensed imagery in mapping American bramble (*Rubus cuneifolius*). South African Geographical Journal **100**(3) 291-307.

RAMOELO, A CHO, M MATHIEU, R and SKIDMORE AK (2015) Potential of Sentinel-2 spectral configuration to assess rangeland quality. Journal of Applied Remote Sensing **9** 1–11.

REBELO, A GOKOOL, S HOLDEN, P and NEW M. (2021) Can Sentinel-2 be used to detect invasive alien trees and shrubs in Savanna and Grassland Biomes? Remote Sensing Applications: Society and Environment **23**.

SCHULZE (ED.) RE (2007) South African Atlas of Climatology and Agrohydrology. Pretoria, South Africa.

SHELESTOV, A LAVRENIUK, M KUSSUL, N NOVIKOV A and SKAKUN S (2017) Exploring Google Earth Engine Platform for Big Data Processing: Classification of Multi-Temporal Satellite Imagery for Crop Mapping. Frontiers in Earth Science **5**.

SIBANDZE, P (2010) Spectral differentiation of *Cannabis sativa* l from maize using hyperspectral indices. Unpublished MSc Thesis. University of KwaZulu-Natal, Pietermaritzburg, KwaZulu Natal, South Africa.

SIDHU N, PEBESMA E and CÂMARA G (2018) Using Google Earth Engine to detect land cover change: Singapore as a use case. European Journal of Remote Sensing **51**(1) 486-500.

SILLERO N, ARENAS-CASTRO S, ENRIQUEZ-URZELAI U, VALE CG, SOUSA-GUEDES D, MARTÍNEZ-FREIRÍA F, REAL R and BARBOSA AM (2021) Want to model a species niche? A step-by- step guideline on correlative ecological niche modelling. Ecological Modelling **456**.

STONE R (2022) It seems amaMpondo *Cannabis* farmers will be left behind in the green gold rush. Mail and Guardian. 1 March 2022 South Africa.

SUJUD, L HAADI, J HASSAN, MAJ and ZURAYK R (2021) *Cannabis* detection from optical and RADAR data fusion: A comparative analysis of the SMILE machine learning algorithms in Google Earth Engine. Remote Sensing Applications: Society and Environment **24**.

TASSI A and VIZZARI M (2020) Object-Oriented LULC Classification in Google Earth Engine Combining SNIC, GLCM, and Machine Learning Algorithms. Remote Sensing **12**.

XUE, J and BAOFANG S (2017) Significant Remote Sensing Vegetation Indices: A Review of Developments and Applications. Journal of Sensors.

YEOM J, JUNG, J CHANG A, ASHAPURE A, MAEDA M, MAEDA A and LANDIVAR J () Comparison of Vegetation Indices Derived from UAV Data for Differentiation of Tillage Effects in Agriculture. Remote Sensing **11**. doi:10.3390/rs11131548.

CHAPTER 3 WATER USE MEASUREMENTS OF *CANNABIS SATIVA* IN KWA-ZULU NATAL – FIELD TRIALS

Authors: Gary Denton and Alistair Clulow

3.1 KwaZulu-Natal commercial field measurements background

Cannabis sativa L. is grown under diverse conditions in both temperate and tropical environments (Cosentino et al., 2012; Clarke and Merlin, 2016). It was declared illegal in South Africa in 1928 (Perkel, 2005), however since 2018, legislation allows for the private cultivation and consumption of small amounts of cannabis (Institute for Economic Justice, 2023). Prade et al. (2011) summarised that *Cannabis sativa* L. is grown in the USA, Ireland, Spain, Germany, and Poland for biofuel purposes. Its history within South African legislation is summarised in a report by the United Nations Office on Drugs and Crime (2002), which states that cannabis cultivation in South Africa has been identified to be most prevalent in the provinces of the Eastern Cape and KwaZulu-Natal.

Cannabis sativa L. is divided into two subspecies depending on their chemical composition and hence their usage. *C. sativa* L. is classified as hemp if the delta-nine-tetrahydrocannabinol (THC) content is less than 0.3%, whilst a THC percentage higher than 0.3% classifies the plant as marijuana (Wimalasiri et al., 2021). While hemp is grown for agricultural purposes (fibre and seed) and medicinal applications (cannabidiol and oil), marijuana is typically grown for personal consumption. Hemp is reported as being a high yielding multi-purpose crop with low inputs (Struik et al., 2000). However, water and nitrogen deficiencies are two major constraints facing the hemp cultivation industry (Cosentino et al., 2013; Tang et al., 2017). Nitrogen deficiency is typically addressed through application of appropriate fertilizers for optimum growth (Cosentino et al., 2007; Campiglia, Radicetti and Mancinelli, 2017; Tang et al., 2017), whereas water deficiency is addressed through irrigation. The implementation of irrigation schedules accompanying precision agriculture, requires knowledge regarding the crop water use, however, literature recommendations for the water requirements (henceforth known as evapotranspiration) of hemp are ambiguous: in a global summary provided by Pejic et al. (2018), hemp requires 250 – 280 mm in Ukraine, citing Kisgeci (1994); in the Netherlands hemp is claimed to require at least 650 mm rainfall, citing Van Dam (1995); in Tasmania, Australia, hemp requires 535 mm over a growing cycle, citing Lisson and Mendham (1998); and Bocsa and Karus (1998) reported ET of up to 700 mm in eastern Europe over the growing season. Unfortunately, all these studies cited by Pejic et al. (2018) were either not peer-reviewed or were inaccessible and could therefore not be verified.

A study by Cosentino et al. (2013), noted an ET of 320 mm over a full growing season of hemp in a semi-arid Mediterranean climate, while Bajić et al. (2022) observed that hemp's ET ranged from 450 to 520 mm over a two-year period, across three hemp variants in Serbia. Both these studies applied the Class-A pan reference evaporation method by estimating a Kc to estimate ET. However, Bajić et al. (2022) obtained Kc from Cosentino et al. (2013) who did not specify how Kc was estimated. This means that Kc cannot be validated, potentially leading to discrepancies in ET calculations for both studies. Thevs and Aliev (2022) used sap flow measurements and found that hemp's ET was 353 mm in northern Kazakhstan over the growing season; since sapflow measurements were spatially and temporally limited, measurement data were extrapolated to fill in data gaps. Thevs and Nowotny (2023) found that ET averaged 343 mm over a four-year trial in northern Germany using the S-SEBI remote sensing model but lacked *in-situ* data and validation. However, the ET of hemp has not been measured using the eddy covariance technique, which remains one of the most steadfast methods of ET measurement, offering non-intrusive, direct measurement at a high temporal resolution (Burba, 2021).

The lack of sufficient scientifically sound information on hemp ET is particularly problematic in water scarce countries such as South Africa (Otieno & Ochieng, 2004) where there is the potential for significant expansion of the hemp industry. This study focused to determine the ET of hemp using *in-situ,* field-based measurements and provides estimates of Kc, so that the ET of hemp can be estimated across different climates in different parts of the world using the internationally accepted FAO-56 Penman-Monteith method (Allen et al., 2006). As ET estimation incorporates the conjunctive use of a crop coefficient and reference evaporation, the influence of the local climate, specific to the study's area, is included, allowing for the calculation of ET specific to that region.

3.1.1 Study site description and relevant maps

The study site (29°31'37.0" S, 30°28'03.2" E) was located on a commercial farm near Pietermaritzburg in the province of KwaZulu-Natal, South Africa (Figure 3-1). A seven-ha area of *Cannabis sativa* L. was planted in late November 2022 and was managed, weeded and irrigated by the local farming business. An electrified fence surrounded the site for security purposes.

The crop was partitioned into three fields, to the North, East, and South sides. The South field contained feminized *C. sativa* L. seedlings (landrace: Charlotte's Angel), while the other two plots (North, East) contained *C. sativa* L. clones (landrace: Cherry Blossom; Figure 3-2).

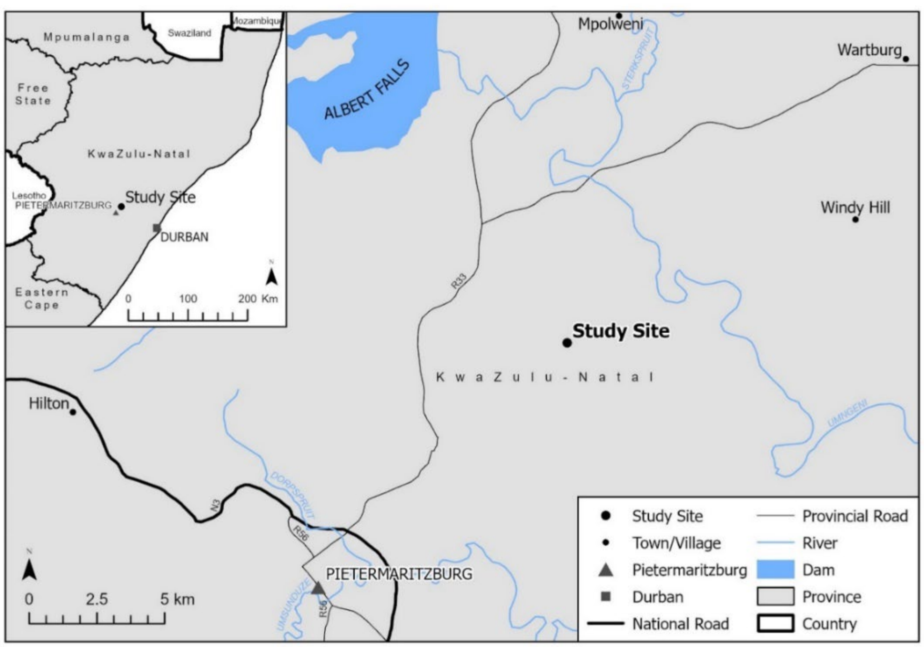


Figure 3-1 Trial site situated within KwaZulu-Natal, South Africa

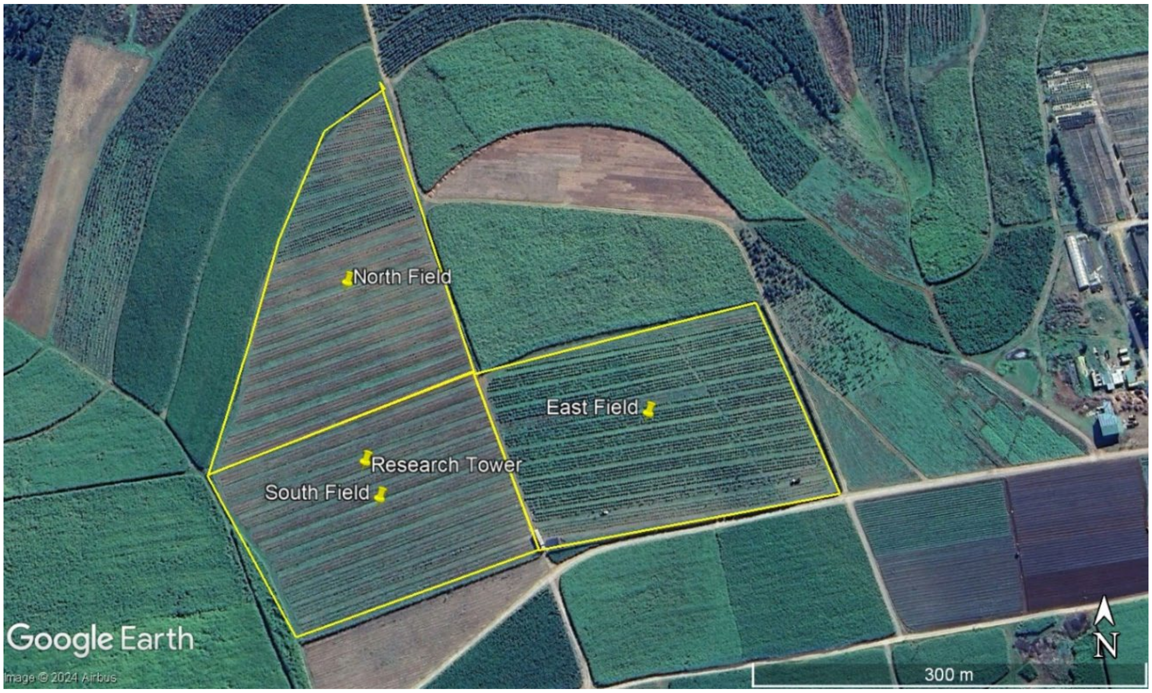


Figure 3-2 The three hemp fields and position of the measurement tower (Google Earth image, accessed 05/08/2024)

Seeds and clones were germinated in a greenhouse prior to being transplanted (Figure 3.3 and 3.4). Seedlings were transplanted into the South field on 21 November 2022, while clones were transplanted into the East field on 22 November 2022 and into the North field on 28 November 2022. The crops were irrigated using dripper irrigation lines (Figure 3.5 a), with a dripper applied 0.05 m away from each plant stem to avoid stem rot (Figure 3.5 b). Fertigation was applied through the irrigation lines. Plants within rows were spaced approximately 2 m apart, while the row-spacing was approximately 2.5 m (Figure 3.5 c). Every fifth row was left fallow and used as a tram line for tractors to move through when spraying (Figure 3.5 d). In the South field, after plants had grown over 1 m tall, they were 'topped', which involves removing their apex to slow the plant's vertical growth and encourage secondary branching. This is a management strategy that encourages a higher concentration of flowers to form before being harvested. The buds were harvested on 15 April 2023.

a

Figure 3-3 Hemp seedling germinated in a greenhouse

b

Figure 3-4 Trays containing hemp seedlings under shade cloth

Figure 3-5 (a) Experimental site containing hemp; (b) hemp plants with research tower in the background; (c) view from the top of the research tower looking from the South field towards the East field. Note both sapling and row spacing; and (d) hemp plants with research tower in the background.

The underlying soil texture information was obtained using the Soil and Terrain Database (SOTER) for South Africa, an international database of information on soil and terrain properties (Batjes, 2004). The South African database was downloaded and imported into QGIS (version 3.28.11), where the soil category for the local farming business was determined. This soil category, within the SOTER database contained codes for their associated landform, lithology and soil texture that were matched according to Batjes (2004) and Dijkshoorn, van Engelen and Huting (2008). As such, the research site fell on soils that are well drained, with approximately 74% sand, 5% silt and 21% clay within the top 0.2 m of the soil profile and can therefore be considered as a sandy clay loam.

A field specific soil fertility analysis was conducted and the elements within the soil profile across the three fields are summarised in Table 3-1 with their corresponding reference locations (Figure 3-6). Reference points 5193, 5195 and 5200 occur in the South, North and East fields, respectively (Figure 2.2).

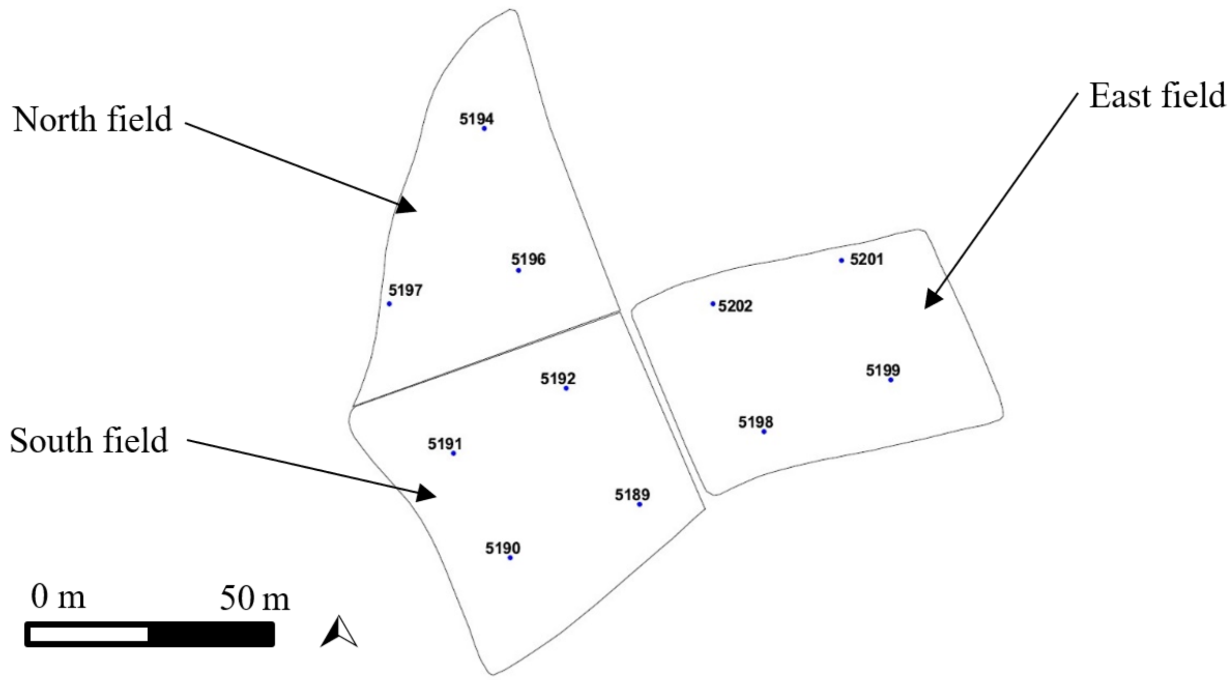


Figure 3-6 Location of soil sample reference numbers (source: Local farming business)

Table 3-1 Summary of soil elements across the three fields taken in August 2022 (source: local farming business)

Lab no	Reference no	pH	Pbray I	K	Na	Ca	Mg	Ex Acid KCL	%Ca	%Mg	%K	%Na	Acid Sat	Ca: Mg	(Ca+Mg)/K	Mg: K	S-Value	Na: K	CEC	Density	Sulphur	Zn	Mn	Cu	Fe
		-	mg/kg			mg/kg		cmol (+)/kg		%			%	1.5-4.5	10.0-20.0	3.0-4.0	cmol (+)/kg	-	cmol (+)/kg	g/cm3	mg/kg		mg/kg DTPA		
G30-40377	AT-VTPU05189	5.5	28	366	26	2532	568	0	68.92	25.37	5.1	0.61	0	2.72	18.5	4.98	18.37	0.12	18.37	0.93	20.47				
G30-40378	AT-VTPU05190	5.16	23	381	15	1854	467	0	65.57	27.08	6.88	0.47	0	2.42	13.46	3.93	14.14	0.07	14.14	0.97	13.92				
G30-40379	AT-VTPU05191	4.63	26	231	17	1372	407	0	63.14	30.73	5.45	0.68	0	2.05	17.23	5.64	10.87	0.13	10.87	0.98	24.05				
G30-40380	AT-VTPU05192	5.06	20	242	20	1789	527	0	64.02	30.92	4.44	0.62	0	2.07	21.39	6.97	13.97	0.14	13.97	0.96	14.55	3.94	46.18	3.24	89.37
G30-40381	AT-VTPU05193	4.98	21	249	22	1697	498	0	63.81	30.68	4.79	0.71	0	2.08	19.71	6.4	13.3	0.15	13.3	0.96	17.28				
G30-40382	AT-VTPU05194	5.46	36	330	21	1868	518	0	64.34	29.23	5.82	0.62	0	2.2	16.09	5.03	14.52	0.11	14.52	0.99	9.84	3.44	38.86	2.78	68.99
G30-40383	AT-VTPU05195	5.16	19	237	25	1886	591	0	62.92	32.33	4.04	0.71	0	1.95	23.59	8.01	14.99	0.18	14.99	1.07	14.42				
G30-40384	AT-VTPU05196	5.39	39	377	28	2037	480	0	66.96	25.89	6.34	0.8	0	2.59	14.64	4.08	15.21	0.13	15.21	1.03	11.09				
G30-40385	AT-VTPU05197	4.84	22	271	38	1770	476	0	65.02	28.68	5.1	1.2	0	2.27	18.39	5.63	13.61	0.24	13.61	0.95	20.1				
G30-40386	AT-VTPU05198	4.7	43	261	28	1533	449	0	63.16	30.35	5.49	1	0	2.08	17.02	5.53	12.13	0.18	12.13	1.02	39.96				
G30-40387	AT-VTPU05199	5.12	35	201	24	1195	360	0	62.58	30.94	5.37	1.11	0	2.02	17.4	5.76	9.54	0.21	9.54	1.06	27.07	3.71	32.85	3.07	67.88
G30-40388	AT-VTPU05200	5.54	64	332	33	1735	485	0	63.58	29.16	6.21	1.05	0	2.18	14.92	4.69	13.64	0.17	13.64	1.08	96.94				
G30-40389	AT-VTPU05201	4.53	51	258	26	1260	332	0	64.32	27.8	6.75	1.13	0	2.31	13.65	4.12	9.79	0.17	9.79	1.06	49.2				
G30-40390	AT-VTPU05202	4.12	22	176	23	998	283	0.87	57.16	26.58	5.14	1.14	9.99	2.15	16.29	5.17	7.86	0.22	8.73	1.04	64.91				

3.1.2 Measurement Approach

To determine total ET, an eddy covariance system (EC150 EasyFlux, Campbell Scientific, Logan, Utah, USA; Figure 3.7) was installed in the South field on a lattice mast, positioned in consideration of the dominant wind direction to optimize the fetch, ensuring at least 100 m of hemp crop in the upwind direction.

Figure 3-7 Eddy covariance system installed on a 6 m tall lattice mast

Net irradiance (CNR4, Kipp and Zonen, Delft, Netherlands) was measured on site above the canopy. To measure the flux of H_2O over the crop canopy, an open path gas analyser (EC150, Campbell Scientific, Logan, Utah, USA) and sonic anemometer (CSAT3A, Campbell Scientific, Logan, Utah, USA) were used (Figure 3.8 a and b). They were attached to the mast and maintained at a height of approximately 2 m above the average crop height. Latent Energy (Eqn. 3.1) was calculated as follows:

$$LE = \lambda \left((Mw / Ma) / p \right) \rho \, w \, e \qquad [3.1]$$

where LE was calculated by multiplying the latent heat of vaporisation (*λ*) by the ratio of molar masses of water and air, using water vapour pressure (*e*), wet air density (*ρ*), atmospheric pressure

(p), and instantaneous wind speed (w). The standard coordinate rotations and corrections were applied on the datalogger (Campbell Scientific, 2018).

A fine wire (FW) thermocouple (FW1 Type E, Campbell Scientific, Logan, Utah, USA) with a diameter of 25 µm was attached to the CSAT3A for high frequency air temperature measurement. Rainfall was measured (TE525, Texas Instruments, Dallas, Texas, USA) and rainfall gaps over a period of 3 weeks, due to a blocked raingauge, were patched using rainfall data from a raingauge 16 km from the site, which had a similar daily rainfall (R^2 = 0.82). A temperature and relative humidity sensor (HC2S3, Campbell Scientific, Logan, Utah, USA) was placed in a radiation shield (41003-5, Campbell Scientific, Logan, Utah, USA) at a height of 2 m above the canopy. The EC150, FW, HC2S3 and CSAT3A measurements were sampled at a frequency of 10 Hz using a datalogger (CR3000, Campbell Scientific, Logan, Utah, USA) and averaged at 30-min timestamps. Instruments used are summarised in Table 3.2.

Volumetric Water Content (VWC) of the top 0.6 m of the soil profile was measured using three water content reflectometers (CS616, Campbell Scientific, Logan, Utah, USA), that were placed within the row but away from the dripper line points. The three reflectometers were placed at depths of 0.15 m, 0.3 m, and 0.6 m (Figure 3.9).

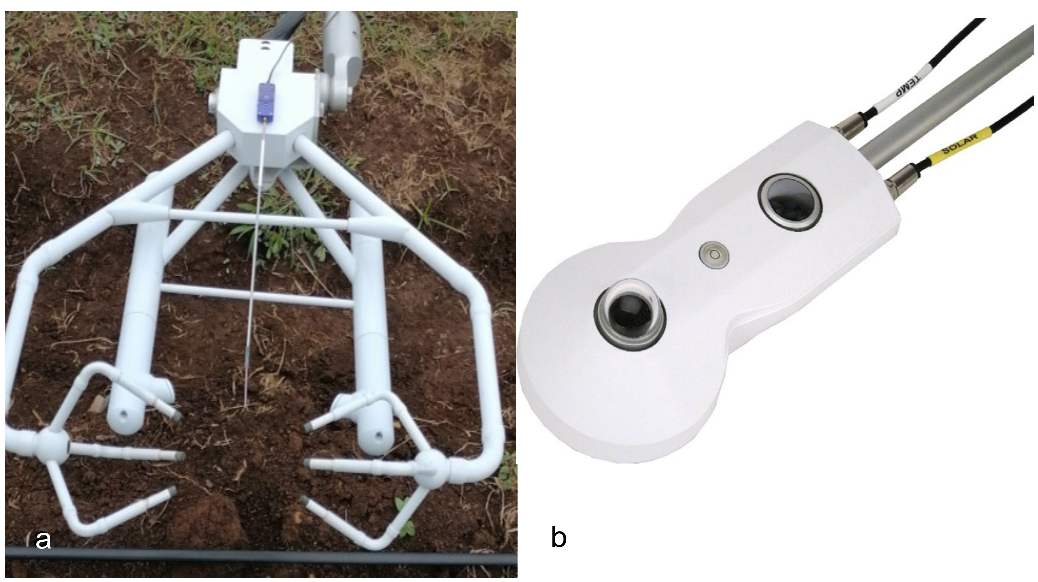


Figure 3-8 (a) Sensors including the CSAT3A, EC150 & FW1 attached together, (b) four component net radiometer.

Reference evapotranspiration (ETo) was calculated using the FAO-56 Penman-Monteith method (Allen et al., 2006). An hourly formula, including small night-time values, was used from data collected at the flux tower to obtain ETo and to determine a monthly crop factor.

Figure 3-9 Soil volumetric water content probe to measure soil water profile

3.2 Results

The average temperature over the growing season was 20.3°C (Figure 3.10 a), with a minimum air temperature of 10.2°C and maximum of 35.6°C occurring due to high incoming shortwave radiation. A period of high temperatures was observed in January 2023 with maximum daily temperatures remaining above 30°C for a two-week period. A gradual trend of decreasing minimum temperature associated with decreasing solar radiation was observed towards the end of the summer season, with April having the lowest monthly average minimum temperature over the season (17.8°C). Throughout the growing season, daily solar radiation averaged 13.5 MJ m^{-2} day^{-1}, with April having the lowest monthly average solar radiation (12.9 MJ m^{-2} day^{-1}).

The average daily wind speed fluctuated between 2.2 m s^{-1} in the first half of the season, and 1.8 m s^{-1} in the second half (Figure 3.10 b). Storms occurred on 20 February, where high wind speeds reached 3.4 m s^{-1}, with a corresponding shift in wind direction from South-South-West to East-North-East. Daily average wind speed gradually decreased from planting in December to harvest in April, associated with a seasonal transition from mid-summer into autumn. The daily vector average wind direction was approximately 200° or from the south-south-west in which there was approximately a fetch of 105 m over the hemp crop.

Table 3-2 Instruments included in the eddy covariance system

Instrument	Measurement	Manufacturer
CS616 Water Content Reflectometers	Volumetric soil water content	Campbell Scientific, Logan, Utah, USA
EC150 CO_2/H_2O Open-Path Gas Analyser	CO_2/H_2O flux	Campbell Scientific
HFP01 Soil Heat Flux Plate	Ground heat flux	Huxaflux, Delft, Netherlands
CSAT3A Three-Dimensional Sonic Anemometer	CO_2/H_2O flux	Campbell Scientific
TE525mm Tipping Bucket Rain Gauge	Rainfall	Texas Instruments, Dallas, Texas, USA
HC2S3 Temperature and Relative Humidity Probe	Temperature; relative humidity	Campbell Scientific
CNR4 Net Radiometer	Net solar radiation	Kipp and Zonen, Delft, Netherlands
FW1 Type E fine wire thermocouples	Air temperature	Campbell Scientific
TCAV Type E thermocouples	Average soil temperature	Campbell Scientific

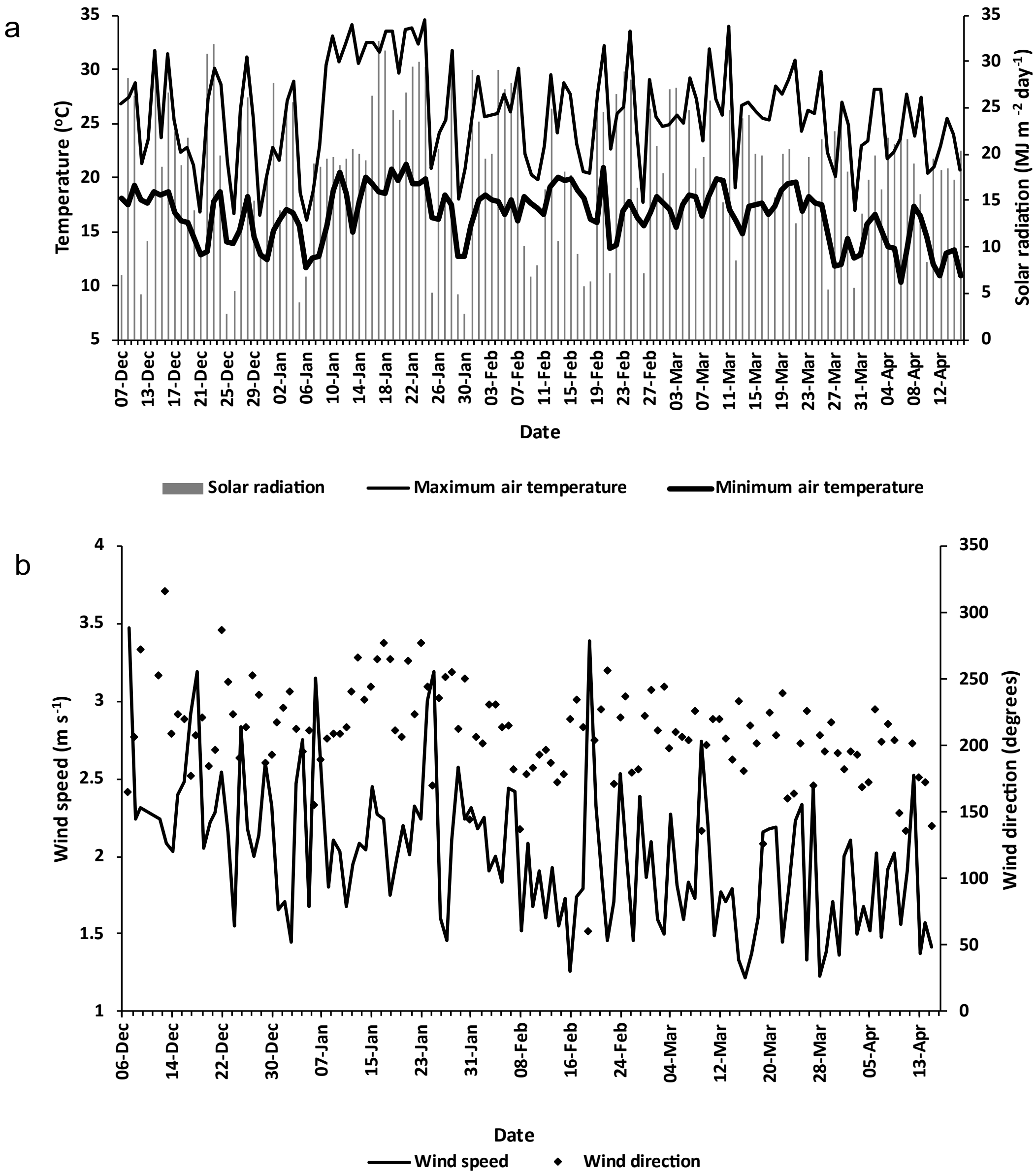


Figure 3-10 (a) Minimum and maximum air temperature and solar radiation; (b) average daily wind speed and direction

The first six days of daily rainfall in December were not measured as the eddy covariance system was installed on 7 December 2022, yet December had the highest monthly rainfall (204 mm) over the growing season and April had the lowest (23.6 mm). As the crop was harvested halfway through the month (15 April 2023), only half a month of rainfall data was collected. The highest daily rainfall (35 mm) occurred on 29 December (Figure 3.11 a). A dry period was observed between 8 and 26 January where no precipitation occurred. The total rainfall over the growing season was 452 mm.

Drip irrigation was applied throughout the growing season (Figure 3.11 b). The soil water content was monitored using an AquaCheck soil moisture probe, and irrigation was applied accordingly. No irrigation was applied during the months of December due to sufficient rainfall. Irrigation applied was highest in March, totalling 15 L plant^{-1} month^{-1} (1.56 mm plant^{-1} month^{-1}), followed by January

(13.8 L plant^{-1} month^{-1} or 1.4 mm plant^{-1} month^{-1}), February (8.1 L plant^{-1} month^{-1} or 0.8 mm plant^{-1} month^{-1}), with April requiring the least irrigation with only (6 L plant^{-1} month^{-1} or 0.6 mm plant^{-1} month^{-1}).

The volumetric water content throughout the soil profile (measured at 0.15 m, 0.3 m and 0.6 m) was calculated to represent the profile as a whole down to 0.6 m (Figure 3.11 c), which represents the rooting zone. The VWC fluctuated between 20% to 40%, corresponding with rainfall events, throughout the growing season. An increase in VWC (20% to 35%) occurred towards the end of December, due to high rainfall, before decreasing to 15%, at harvest, in April.

The average daily ET over the measurement period was 2.9 mm (Figure 3.12) with a maximum of 6.9 mm. High variability in ET values were observed between December and March, due to fluctuations in weather conditions (Figure 2.3 a), with values stabilizing and dropping as autumn progressed. Days with higher ET corresponded to hot, dry periods such as 9 to 12 January (remaining between 5 mm day^{-1} and 6 mm day^{-1}) and 20 February 2023 (7 mm day^{-1}). A summer thunderstorm occurred on 30 January with high wind speeds and hail, incurring damage (Figure 3.13), broken branches and lodging of plants, with plant stems remaining bent over. The average water required to grow a hemp tree in the South field was 28.4 L day^{-1} tree^{-1} (2.94 mm plant^{-1} day^{-1}). This includes the water used by the weeds and that evaporated from the soil surface area around each plant which cannot be excluded from the water use of the crop in a field setting.

Due to the location of the eddy covariance system and the predominant wind direction being from the south (Figure 3.14 b), the area contributing to the measurements was primarily the South field. Plant dimensions and LAI were therefore recorded for the South field. However, to showcase the difference between genetic variation of seedlings and clones, the plant diameters and LAI of the North field (clones) were included as a comparison to the South field (seedlings). The measurement of plant diameter and LAI began on growing day 24, after the seedlings had been established, but the data portrayed in Figure 3.14 a, b and c starts from growing day 20, to provide a clearer visual representation. In a comparison of LAI, height and width of plant canopy between the North and South fields (Figure 3.14 a, b, c), the earliest measurements of LAI (Figure 3.14 a) included weeds, which were removed during the early growth of the crop.

This leads to an overestimation of LAI-values particularly early in the growing season. This is supported by the decrease in LAI from growing day 24 to 36 (North field), and the growing day 38 to 50 (South field). Once in the rapid growth phase, the LAI increased from 0.5 to 0.9 for both fields over a period of approximately six weeks. The South field LAI was higher than that of the North field in January (0.59 and 0.52, respectively) but slightly lower by the end of February (0.87 and 0.89, respectively).

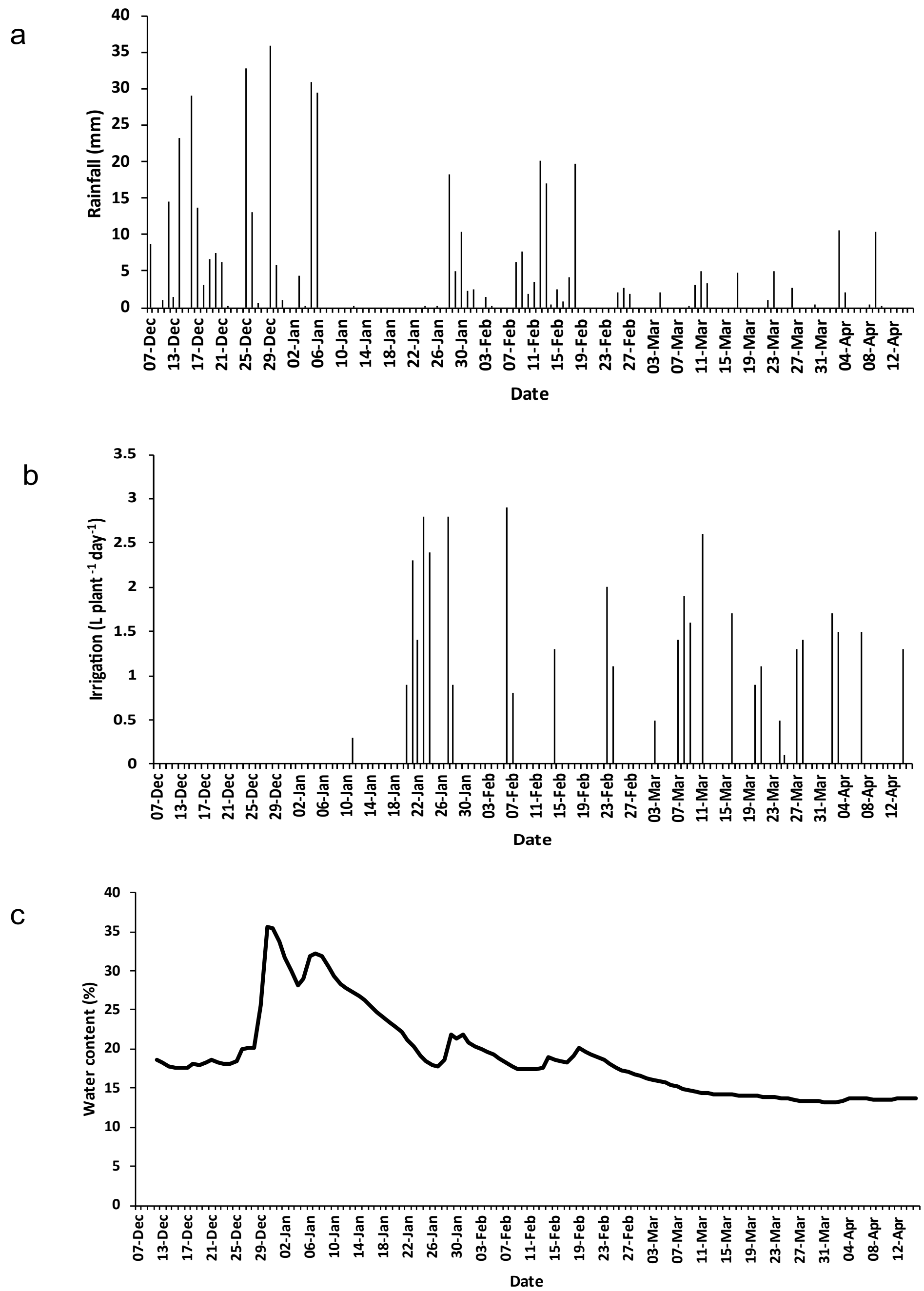


Figure 3-11 (a) Daily rainfall; (b) irrigation applied over the growing season; and (c) average VWC throughout the soil profile

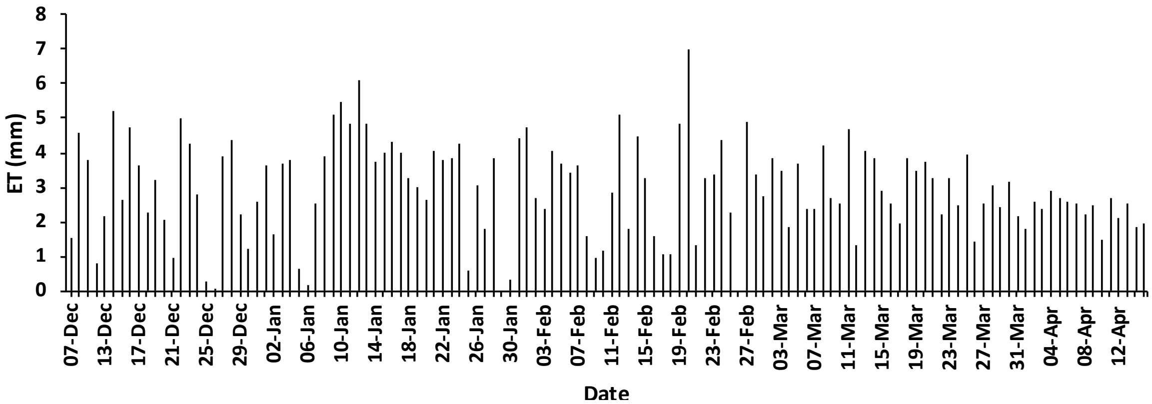


Figure 3-12 Daily ET between December and April

The South field plants (seedlings) were consistently taller than the North field plants (clones; Figure 3.14 b), and reached a height of 1 600 mm, while the North field plants reached a maximum height of 800 mm at the time of last measurement. If this is extrapolated to harvest, it suggests a final height of approximately 1 000 mm, still less than the canopy height of the South field plants.

Figure 3-13 Damaged and broken plants, on 30 January 2023, due to hail

The plant canopy width increased over time, with the South field plants consistently measuring higher aerial canopy cover than the North field plants (Figure 3.14 c). The largest increase in plant canopy width was observed in the South field, where it grew from 766 mm on day 50 to 1 284 mm on day 73. The North field showed similar growth from 538 mm on day 59 to 985 mm on day 81. The final canopy diameter of the hemp canopy in the South field was 1 500 mm, while the North field plants were 1 000 mm.

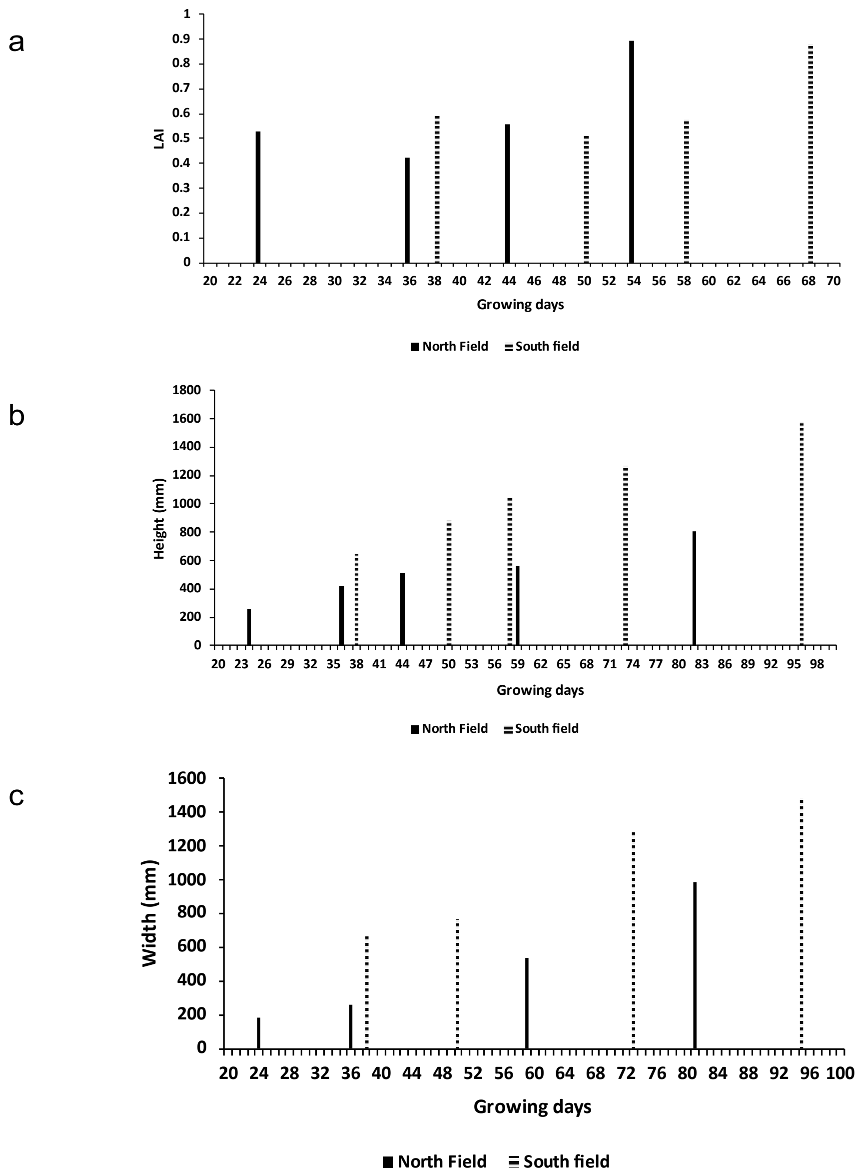


Figure 3-14 (a) LAI of hemp plants; (b) plant height of South field and North field over the growing season; and (c) plant width of North and South field crops over the growing season

Reference evapotranspiration in December and January fluctuated due to variations in weather conditions in the summer rainfall area. High ETo values were observed in mid-January (Figure 3.15 a), peaking at 7.2 mm on 24 January. These higher values correspond with a period of clear skies (Figure 3.15 a) and no rainfall (Figure 3.11 a). Daily average ETo values were lower but more consistent during the month of April compared to December and January, due to the onset of autumn, with lower, but more consistent daily solar irradiance (Figure 3.10 a).

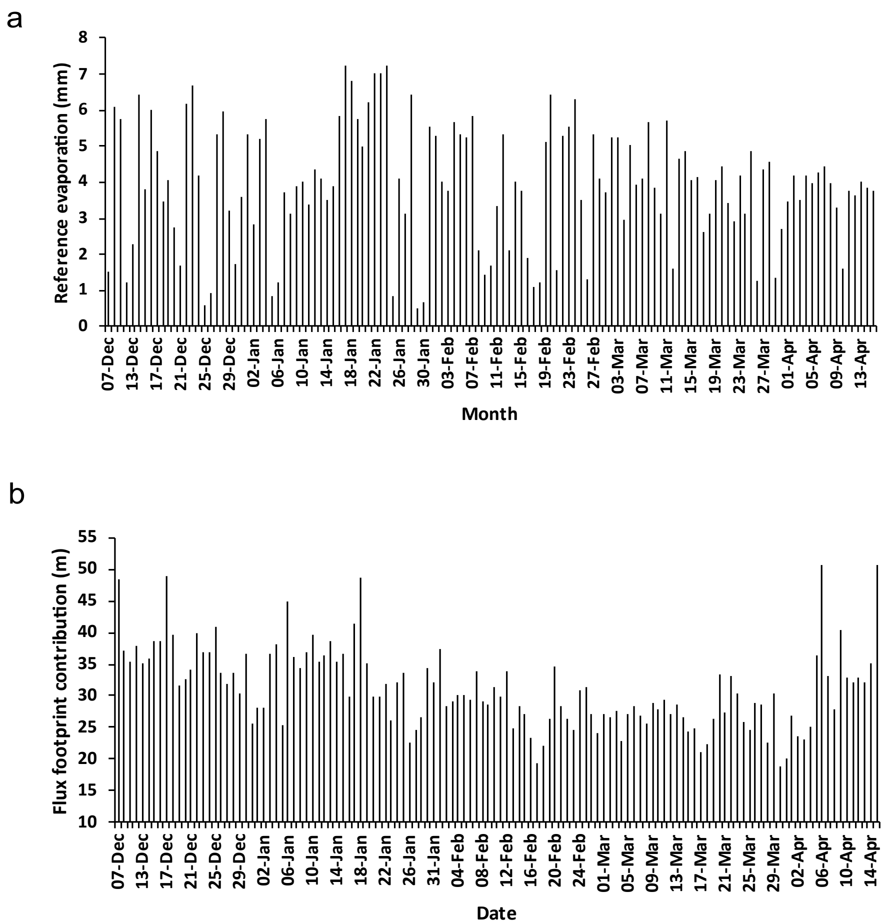


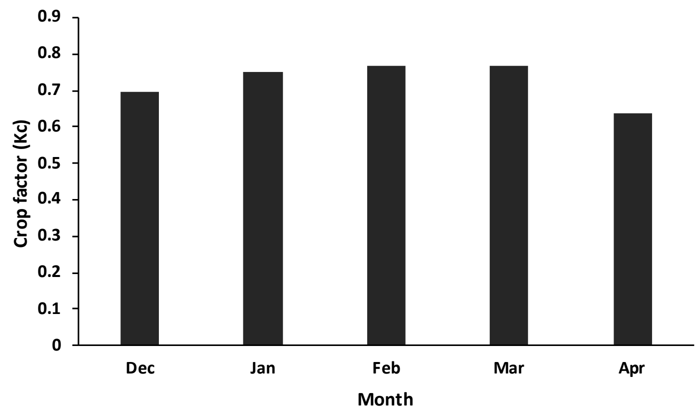
Figure 3-15 (a) Reference evaporation of the hemp crop between December and April; and (b) distance from the research tower that had the maximum effect on ET estimates

The flux footprint represents the distance from the research tower where maximum evapotranspiration occurs. The distance of maximum contribution to measurements remained typically within 20 m to 50 m from the research tower (Figure 3.15 b), until April 2023 where the daily flux footprint variability increased. This was in part due to raising the height of the EC system sensors at the beginning of April from 2.8 m to 3.3 m above the soil surface, to keep it approximately 2 m above the crop canopy to accommodate plant growth, as recommended by international literature (Burba, 2021). Although the distance of maximum contribution to flux measurements increased, there was a sufficient fetch of hemp crop to ensure that this did not affect ET measurements. The maximum distance of upwind contribution to the flux footprint indicates that the majority of the flux measurements were derived from the hemp crop or the South field.

The monthly crop coefficient (Figure 3.16 a) increased from planting in December (0.69) to a peak in March (0.76). The crop factor was lower in April (0.63). Harvest took place on 15 April 2023, and as such only half a month of data was collected for April, potentially causing a slight underestimation of measurement. The average crop factor over the season was 0.72.

The North field, containing clones, produced a higher bud yield of 6 359 kg ha^{-1} at the time of harvest (Figure 2.8 b), whilst the South field bud yield was lower, at 3 623 kg ha^{-1}. The clones (North field) had a higher overall yield compared to that of the seedlings (South field) as the plant density of the South field at harvest was 1 035 plants ha^{-1}, while the North field had a harvest density of 2 000 plants ha^{-1}. Although both fields had an initial planting density of 2 000 plants ha^{-1}, the South field density was almost half that of the North field at time of harvest due to the removal of male hemp plants that needed to be removed to prevent cross-pollination. This significant difference in plant density, size and yield highlights the importance of planting strategy and seed or shoot stock used in hemp farming.

a



b

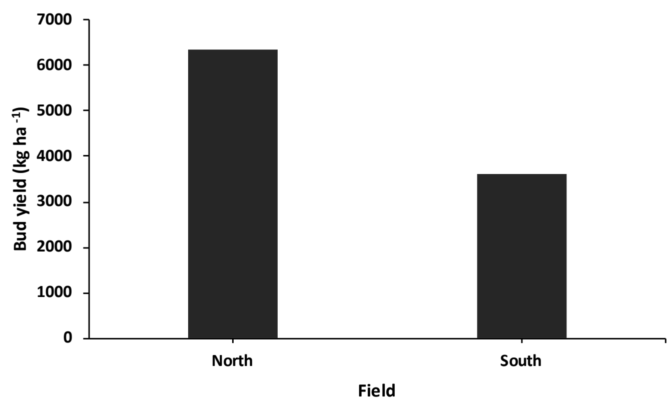


Figure 3-16 (a) Monthly crop coefficient of hemp; (b) total bud yield per hectare harvested at the end of the growing season

The water productivity (WP), which requires measurement of ET, was calculated for the South field, as the research tower was placed within that field, with the fetch falling primarily from this field. The WP of the South field plants represent the mass of bud produced per cubic metre of water lost to ET and was found to be 0.96 kg m^{-3}.

3.3 Discussion

The daily ET fluctuated from planting in November until March, due to the high variability in daily temperatures, solar irradiance, and rainfall, after which it was more stable. Comparative studies report daily water consumption as a synonym for daily ET (Cosentino et al., 2013; Thevs and Aliev, 2022; Thevs and Nowotny, 2023). However, Cosentino et al. (2013) calculated crop water use, rather than ET, by measuring irrigation, precipitation, and gravimetric soil water content before and after each irrigation event. Thevs and Aliev (2022) used sapflow measurements to calculate hemp ET, while Thevs and Nowotny (2023) used remote sensing techniques (Simplified Surface Energy Balance Index (S-SEBI) model) to estimate crop ET. The total ET of the hemp crop in the present study was 377 mm over the growing season (Figure 3.12), which is similar to that recorded by Thevs and Aliev (2022), who observed an ET of 353 mm over the growing season in northern Kazakhstan, for the hemp variety Santina 70. However, Thevs and Aliev (2022) used sapflow measurements, which measures hemp transpiration and does not include surrounding weeds, as was the case in the present study. Sapflow and EC measurements have different strengths and limitations, and neither method should be considered better than the other. For example, sapflow measurements do not account for evaporation from soil and canopy interception, and therefore do not represent total ET (Wilson et al., 2001). Evapotranspiration in the present study was similar to the findings of Thevs and Nowotny (2023), who observed an average of 343 mm ET over a four-year trial (April-October annually; 2018-2021) in northern Germany, with the study's highest annual ET of 407 mm occurring in 2019. Cosentino et al. (2013) found a water use of 327 mm for the hemp variety Futura 75 in southern Italy, but this was not a direct measurement of ET. In the present study, ET of the hemp crop peaked in mid-February at 6.9 mm day^{-1}, before decreasing steadily until harvest, which is similar to Thevs and Nowotny (2023), who observed a peak ET of 6 mm day^{-1} after which ET steadily decreased until harvest. Although Cosentino et al. (2013), Thevs and Aliev (2022), and Thevs and Nowotny (2023) all utilise a completely different approach to the present study, they had comparable temperature regimes during the growing season (15°C to 20°C). However, Cosentino et al. (2013) and Thevs and Aliev (2022) both utilised drip irrigation, while Thevs and Nowotny (2023) did not apply irrigation at all.

Rainfall over the study site totalled 452 mm over the growing period (Figure 3.11 a) and was higher than evapotranspiration (377 mm), with December having the highest monthly rainfall (204 mm) and April having the lowest (24 mm). According to Struik et al. (2000) the marketable value for non-irrigated hemp drops drastically when precipitation drops below 300 mm by placing the plant under water stressed conditions. The period of 8 to 26 January had large rainfall gaps in which irrigation took place when required (Figure 3.11 b). As a result, the VWC within the top 0.6 m of the soil profile was relatively high throughout the soil profile (Figure 3.11 c), ensuring the prevention of water-stressed conditions. Excess rainfall at the beginning of the growth season corresponded with the increase in VWC in January (up to 35%), before maintaining a VWC of 15% between March and April. It should be noted that these results are for a well-watered crop that did not experience water stress.

Sufficient fetch is commonly a challenge with EC measurements. The maximum flux footprint represents the distance from the research tower where the maximum influence on ET originates. The maximum flux footprint was observed to remain between 20 m to 50 m from the research tower (Figure 3.15 b) until April 2023, where the flux footprint increased with higher daily variability occurring. There was no noticeable change in the average wind speed over this period (Figure 3.10 b), and therefore footprint variability is likely due, in part, to the raising of the height of the EC system sensors from 2.8 m to 3.3 m above the soil surface at the beginning of April, to keep it approximately 2 m above the crop canopy to accommodate plant growth as recommended by Burba (2021) for all crop types. Flux footprint is influenced by instrumentation height, canopy height, wind speed, friction velocity, thermal stability, surface roughness and zero-plane displacement (Schuepp et al., 1990; Burba, 2021). The maximum flux footprint extent increases with increased sensor height, while the magnitude of the peak contribution is reduced. The surface roughness coefficient would have increased as the plant height increased, and this could have affected the flux footprint. In this research the daily vector average wind direction was approximately 200°, or from the south-south-west, in which there is approximately a fetch of 105 m over the hemp crop. As a result, it was concluded that there was negligible influence of both the North and East fields (clones) on ET estimates of hemp due to the wind direction, and that the ET estimates were representative of the South field (seedlings). The daily average wind speed over the hemp crop in the first half of the growing season was 2.2 m s^{-1} (Figure 3.10 b), while the second half of the growing season averaged 1.8 m s^{-1} as autumn set in. Some high wind speeds were observed (Figure 3.10 b) and there was lodging of plants (bending of stems near ground level) and hail damage (Figure 3.13), particularly those grown from seedlings in the South field, due to their larger size.

In the present study, the LAI of both the North and South fields were measured, including weeds between hemp plants. The isolation of hemp plants, and thus isolated LAI measurements, did not take place as surrounding weeds and soil surfaces are naturally found in commercial cultivation areas, adding to the water consumption of the field. The LAI was much lower in comparison to previously reported values (Tang et al., 2018; Herppich et al., 2020), and declined in the early stages of the season with the North field declining from 0.52 to 0.42 between the 24th and 36th growing day, while the South field declined from 0.6 to 0.51 during the 38th to 50th growing day (Figure 3.14 a). This is because the earliest measurements of LAI included weeds, which were removed at times, leading to the overestimation of initial values. The initial drop in LAI in both fields could be attributed to the removal of these weeds between the rows. The low LAI of the South field was also impacted by the removal of male hemp plants which were removed to prevent cross pollination with the female hemp flowers and influence the chemical constituents of the bud yield (Malabadi et al., 2023). This caused the plant density to almost halve. Although the utilisation of feminized seed encourages the growth of strictly female plants, the occurrence of males is still possible.

Feminized seed is created through the application of colloidal silver or gibberellic acid to female hemp plants, inducing the formation of male flowers on these plants (Owen et al., 2023). The resulting pollination of another female hemp plant leads to the formation of seed with female chromosomes only, effectively eliminating male genetics. However, this does not guarantee a 100% success rate (Owen et al., 2023), as seen in this study. This is emphasised by the fact that only the South field, containing seedlings, had the occurrence of male hemp plants, whereas the North field, containing clones, did not. In the present study, the harvest density of the North field was 2 000 plants ha^{-1} (in-row spacing of 2 m, inter-row spacing of 2.5 m), while the harvest density of the South field was low, at 1 035 plants ha^{-1} due to the removal of male hemp plants., The North field therefore had a higher bud yield per hectare (6 359 kg ha^{-1}; Figure 2.8 b) than the South field (3 623 kg ha^{-1}). According to a report by Institute for Economic Justice (2023), dry bud for medical cannabis sold at wholesale at approximately ZAR37.4 - ZAR74.8 at the time of writing. Plant height and width of the South field increased quicker than the North field between January and February (Figure 2.6 b and c) due to the removal of male plants, leading to less competition for light, water and nutrients and more space between plants to grow, which in turn increased the risk of lodging. Furthermore, in the present study, plants were 'topped' to encourage lateral growth, additional branching out of the plant and to encourage higher concentrations of flowers to form before harvest.

Water use efficiency (WUE) and WP are internationally accepted agricultural terms, yet there has been a lack of naming consistency in their usage (Sadras et al., 2012). WUE expresses the ratio at which the input of water in the agricultural system reaches the target crop, while WP expresses the water used by the crop compared to the plant biomass produced (Kilemo, 2022). WUE is often incorrectly expressed as the rate of biomass production to water consumed. More specifically, the water productivity of a plant is defined as the harvested plant yield compared to the amount of water consumed (Delauney and Verma, 1993; Herppich et al., 2020), or as the ratio of net CO_2 assimilation rate to transpiration (Lamaoui et al., 2018). A review of the WP values of various crops by Zwart and Bastiaanssen (2004) suggest that it can vary, depending on factors such as climate, irrigation management and soil management. For example, Pejic et al. (2018) cited a number of global studies that indicate hemp WP values differ greatly from place to place, although the study's sources were either not peer-reviewed or were inaccessible and could therefore not be verified. Furthermore, the few reports that do exist on the WP of hemp are difficult to compare since different bases of comparison (bark yield, biomass production, stem dry weight) were used to calculate the WP of the crop (Lisson and Mendham, 1998; Di Bari et al., 2004; Cosentino et al., 2013). Previous studies have tended to focus on hemp production for different reasons, such as fibre (Cosentino et al., 2013; Tang et al., 2016, 2022), stem (Tang et al., 2017) and seed (Tang et al., 2016, 2017), whereas the present study utilised hemp bud production for medicinal purposes. WP can be increased by utilizing lower irrigation techniques (Babaei & Ajdanian, 2020), particularly in arid areas. It has been reported that hemp WP does not change under water deficit stress (Gill et al., 2022), however this conflicts with results by Cosentino et al. (2013), who determined that the WP values of hemp, under non-stressed conditions in a semi-arid Mediterranean environment, was lower compared to the WP of the same crop under water-stressed conditions.

WP values are often influenced by an over-estimation of water transpired by the crop (Cosentino et al., 2007). A study by Cosentino et al. (2013) found that hemp has a WP of 1.91 kg m^{-1} under non-water-stressed conditions in a semi-arid Mediterranean environment. In the present study the WP of 0.96 kg m^{-3} over the growing season was significantly lower. The present study only considered the bud yield weight (Figure 3.16 b), while Cosentino et al. (2013) considered above-ground biomass of the whole plant at harvest. All studies on WUE and WP of hemp use a different basis of comparison, including bark yield, whole above-ground biomass production or stem dry weight (Lisson and Mendham, 1998); Di Bari et al. (2004); Cosentino et al. (2013)). In addition, different management practices are used in the present study (such as topping), depending on the plants' intended use. This is undesirable in bark yield analyses, biomass production and stem dry weight as it causes the hemp plants to remain shorter and shortens the length of plant fibres within the stem (van der Werf et al., 1995). The result is that WP values between studies cannot be compared. It must be noted, however, that the ET used in the derivation of WP in this study includes the ET from the surrounding soil surface and grasses or weeds. This is justified as the presence of bare soil or growth of weeds is unavoidable in commercial cultivation (unless under certain circumstances, such as the surface being covered by plastic sheeting, often not cost effective).

Many crops have prescribed Kc values, that are readily available (Allen et al., 1998). There are, however, only a limited number of studies that provide Kc values for hemp. Studies by Cosentino et al. (2013); Garcia Tejero et al. (2014); Pejic et al. (2018); and Bajić et al. (2022) used Kc with a reference evaporation to estimate water use. Some studies by Nougabi, Shahidi and Hamami (2019); Thevs and Aliev (2022), and Thevs and Nowotny (2023) measured evapotranspiration and calculated Kc for their own trials (located in Iran, northern Kazakhstan and north-east Germany, respectively). In the present study, monthly Kc was calculated through the ratio of ET to ETo. Initial value in December were 0.69, reaching 0.76 between the months of January to March (Figure 3.16 a), before lowering to 0.63 at harvest in April. The crop factor was higher than expected in the first two months of the trial when the hemp plants were small. This is likely due to the rapid growth of weeds, where weeds were bigger than the hemp plants at times until they were removed. After full development of the canopy, from February until harvest in April, the ET estimates and Kc values were more representative of the hemp than the surrounding weeds and soil surface, due to the larger size of the hemp plants than surrounding vegetation, and the periodic removal of this vegetation. These Kc are similar to the results of Thevs and Aliev (2022), whose calculated Kc peaked at 0.7 during their growing season in northern Kazakhstan. In the present study, a decline was observed in the month of April, where Kc dropped to 0.63. This is possibly due to an underestimation taking place, as half a month of measurements took place in April, before harvest took place.

The results of this study determined that the overall water usage was approximately 28.4 L plant^{-1} day^{-1} (2.94 mm plant^{-1} day^{-1}). This is similar to values published by Bauer et al. (2015) who cited "Humboldt County Outdoor Medical Cannabis Ordinance Draft (2010)", stating *Cannabis sativa* L. plants use approximately 22.7 L plant^{-1} day^{-1} in north-western California, however this citation by Bauer et al. (2015) was unattainable by this study. It is further noted by Bauer et al. (2015) that ET data of hemp is limited in the published literature.

Limitations faced during the research included a lack of scientifically based information relating to *C. sativa* L., a high percentage of male plants in the South field (seedlings), lodging of large seedling plants, and variability in seedling plant size. Further research on the wider hydrological impacts and streamflow reduction associated with the cultivation of hemp will enhance our understanding of this versatile crop, its environmental impact, and its economic feasibility.

3.4 Conclusion

There is a global interest in the expansion of areas planted under hemp, however there is relatively little information on water-use and productivity of hemp for decision makers to base their strategies of expansion upon. This is particularly important in water-deficit countries and those replacing existing food crops with hemp. This study provides the first water-use and productivity measurements of hemp grown in South Africa. The water-use over the growing season was higher than comparative studies, and the water productivity of 0.96 kg m^{-3} was lower than other results reported. The crop factor derived in this study agrees with international studies and provides a benchmark for estimating water use of hemp across diverse climatic areas. The crop factor is used in many hydrological models and will enable the assessment of hemp as a streamflow reduction activity in South Africa. The planting density typically used in South Africa was lower than that of international studies. This is significant because the many different uses of the hemp plant have led to different parts of the plant being assessed in terms of WP. A further understanding of the comparison of water productivity to economic productivity, in terms of the water used relative to the rand value of yield produced in South Africa, would benefit growers.

3.5 References

ALLEN R, PEREIRA L, RAES D and SMITH M (1998) Crop Evapotranspiration (guidelines for computing crop water requirements).

ALLEN R, PRUITT W, WRIGHT J, HOWELL T, VENTURA F, SNYDER R, ITENFISU D, STEDUTO P, BERENGENA J, YRISARRY J, and co-authors (2006) A recommendation on standardized surface resistance for hourly calculation of reference ETo by the FAO56 Penman-Monteith method. Agricultural Water Management Elsevier **81** (1–2) 1–22.

BABAEI M and AJDANIAN L (2020) Screening of different Iranian ecotypes of cannabis under water deficit stress. Scientia Horticulturae Elsevier B.V. 260 108904.

BAJIĆ I, PEJIĆ B, SIKORA V, KOSTIĆ M, IVANOVSKA A, PEJIĆ B and VOJNOV B (2022) The Effects of Irrigation, Topping, and Interrow Spacing on the Yield and Quality of Hemp (*Cannabis sativa* L.) Fibers in Temperate Climatic Conditions. Agriculture MDPI **12** (11) 1923.

DI BARI V, CAMPI P, COLUCCI R and MASTRORILLI M (2004) Potential productivity of fibre hemp in southern Europe. Euphytica **140** (1–2) 25–32.

BATJES N (2004) SOTER-based soil parameter estimates for Southern Africa. ISRIC World Soil Information, Wageningen, The Netherlands. Rep. 2004/04, Oct. 2004. Available at: https://www.researchgate.net/publication/40121514

BAUER S, OLSON J, COCKRILL A, VAN HATTEM M, MILLER L, TAUZER M and LEPPIG G (2015) Impacts of surface water diversions for marijuana cultivation on aquatic habitat in four north-western California watersheds. PloS one Public Library of Science **10** (3) e0120016.

BURBA G (2021) Eddy Covariance Method for Scientific, Regulatory, and Commercial Applications. LI-COR Biosciences, Lincoln, Nebraska. URL: www.licor.com

CAMPBELL SCIENTIFIC I (2018) Instruction manual EasyFlux DL CR3000OP For CR3000 and Open-Path Eddy-Covariance System Revision: 3/18. 2018. URL: www.campbellsci.com.

CAMPIGLIA E, RADICETTI E and MANCINELLI R (2017) Plant density and nitrogen fertilization affect agronomic performance of industrial hemp (*Cannabis sativa* L.) in Mediterranean environment. Industrial Crops and Products Elsevier, **100** 246–254.

CLARKE R and MERLIN M (2016) Cannabis Domestication, Breeding History, Present-day Genetic Diversity, and Future Prospects. Critical Reviews in Plant Sciences Taylor & Francis, **35** (5–6) 293–327.

COSENTINO S, PATANÈ C, SANZONE E, COPANI V and FOTI S (2007) Effects of soil water content and nitrogen supply on the productivity of Miscanthus × giganteus Greef et Deu. in a Mediterranean environment. Industrial Crops and Products **25** (1) 75–88.

COSENTINO S, RIGGI E, TESTA G, SCORDIA D and COPANI V (2013) Evaluation of European developed fibre hemp genotypes (*Cannabis sativa* L.) in semi-arid Mediterranean environment. Industrial Crops and Products **50** 312–324.

COSENTINO S, TESTA G, SCORDIA D and COPANI V (2012) Sowing time and prediction of flowering of different hemp (*Cannabis sativa* L.) genotypes in southern Europe. Industrial Crops and Products Elsevier **37** (1) 20–33.

DELAUNEY A and VERMA D (1993) Proline biosynthesis and osmoregulation in plants. Plant Journal Blackwell Publishing Ltd. **4** (2) 215–223.

DIJKSHOORN J, VAN ENGELEN V and HUTING J (2008) Soil and landform properties for LADA partner countries (Argentina, China, Cuba, Senegal and The Gambia, South Africa and Tunisia). URL: www.isric.org

GARCIA TEJERO I, DURAN ZUAZO V, PEREZ-ALVAREZ R, HERNANDEZ A, CASANO S, MORON M and MURIEL-FERNANDEZ JL (2014) Impact of Plant Density and Irrigation on Yield of Hemp (*Cannabis sativa* L.) in a Mediterranean Semi-arid Environment. Journal of Agricultural Science and Technology Journal of Agricultural Science and Technology, **16** (4) 887–895.

GILL A, LOVEYS B, COWLEY J, HALL T, CAVAGNARO T and BURTON R (2022) Physiological and morphological responses of industrial hemp (*Cannabis sativa* L.) to water deficit. Industrial Crops and Products Elsevier, **187** 115331.

HERPPICH W, FLEMMING I, GUSOVIUS H AND DRASTIG K (2020) 'Study of Water Productivity of Industrial Hemp under Hot and Dry Conditions in Brandenburg (Germany) in the Year 2018', Water **12**(11), p. 2982. Available at: https://doi.org/10.3390/W12112982.

INSTITUTE FOR ECONOMIC JUSTICE (2023) Inclusive development in the South African cannabis industry: assessing the challenges. Johannesburg. URL: www.iej.org.za

KILEMO D (2022) The Review of Water Use Efficiency and Water Productivity Metrics and Their Role in Sustainable Water Resources Management. Open Access Library Journal Scientific Research Publishing, **9** (1) 1–21.

LAMAOUI M, JEMO M, DATLA R and BEKKAOUI F (2018) Heat and Drought Stresses in Crops and Approaches for Their Mitigation. Frontiers in Chemistry Frontiers Media S.A., **6**.

LISSON S AND MENDHAM N (1998) Response of fibre hemp (*Cannabis sativa* L.) to varying irrigation regimes. University of Tasmania. Available at: https://hdl.handle.net/102.100.100/547243

MALABADI R, KOLKAR K, CHALANNAVAR R, MUNHOZ A, ABDI G and BAIJNATH H (2023) *Cannabis sativa*: Dioecious into Monoecious Plants influencing Sex Determination. International Journal of Research and Innovation in Applied Science RSIS International, **VIII** (VII) 82–91.

NOUGABIL S, SHAHIDI A and HAMAMI H (2019) Estimation of water requirement and vegetative factor of hemp in different stages of growth. Birjand Plain **34** (4).

OTIENO F and OCHIENG G (2004) Water management tools as a means of averting a possible water scarcity in South Africa by the year 2025. Water SA **30** (5) 668–672.

OWEN L, SUCHOFF D and CHEN H (2023) A Novel Method for Stimulating *Cannabis sativa* L. Male Flowers from Female Plants. Plants Multidisciplinary Digital Publishing Institute (MDPI), **12** (19) 3371.

PEJIC B, SIKORA V, MILIC S, MACKIC K, KOREN A and BAJIC I (2018) Effect of drip irrigation on yield and evapotranspiration of fibre hemp (*Cannabis sativa* L.). Ratar. Povrt. **55** (3) 130–134.

PERKEL C (2005) Cannabis-the debate continues: a South African perspective. South African Psychiatry Rev **8** 25–30.

PRADE T, SVENSSON S, ANDERSSON A and MATTSSON J (2011) Biomass and energy yield of industrial hemp grown for biogas and solid fuel. Biomass and Bioenergy Pergamon, **35** (7) 3040–3049.

SADRAS V, GRASSINI P and STEDUTO P (2012) Status of Water Use Efficiency of Main Crops. URL: https://www.researchgate.net/publication/230626092.

SCHUEPP P, LECLERC M, MACPHERSON J and DESJARDINS R (1990) Footprint prediction of scalar fluxes from analytical solutions of the diffusion equation. Boundary-Layer Meteorology Kluwer Academic Publishers, **50** (1–4) 355–373.

STRUIK C, AMADUCCI S, BULLARD M, STUTTERHEIM N, VENTURI G and CROMACK H (2000) Agronomy of fibre hemp (*Cannabis sativa* L.) in Europe. Industrial Crops and Products Elsevier **11** (2–3) 107–118.

TANG K, STRUIK P, YIN X, CALZOLARI D, MUSIO S, THOUMINOT C, BJELKOVÁ M, STRAMKALE V, MAGAGNINI G and AMADUCCI S (2017) A comprehensive study of planting density and nitrogen fertilization effect on dual-purpose hemp (*Cannabis sativa* L.) cultivation. Industrial Crops and Products Elsevier **107** 427–438.

TANG K, STRUIK P, YIN X, THOUMINOT C, BJELKOVÁ M, STRAMKALE V and AMADUCCI S (2016) Comparing hemp (*Cannabis sativa* L.) cultivars for dual-purpose production under contrasting environments. Industrial Crops and Products Elsevier **87** 33–44.

TANG K, FRACASSO A, STRUIK P, YIN X and AMADUCCI S (2018) Water-and nitrogen-use efficiencies of hemp (*Cannabis sativa* L.) based on whole-canopy measurements and modeling. Frontiers in Plant Science **9** 951.

TANG K, WANG J, YANG Y, DENG G, YU J, HU W, GUO L, DU G and LIU F (2022) Fiber hemp (*Cannabis sativa* L.) yield and its response to fertilization and planting density in China. Industrial Crops and Products Elsevier **177** 114542.

THEVS N and ALIEV K (2022) Water consumption of industrial hemp (*Cannabis sativa* L.) from a site in northern Kazakhstan. Asian journal of water research **8** (2) 19–30.

THEVS N and NOWOTNY R (2023) Water consumption of industrial hemp (*Cannabis sativa* L.) during dry growing seasons (2018–2022) in NE Germany. Journal fur Kulturpflanzen Verlag Eugen Ulmer **75** (7–8) 173–184.

UNITED NATIONS OFFICE ON DRUGS AND CRIME (2002) South Africa Country Profile on Drugs and Crime. https://www.unodc.org/pdf/southafrica/country_profile_southafrica.pdf

VAN DER WERF H, WIJLHUIZEN M and DE SCHUTTER J (1995) Plant density and self-thinning affect yield and quality of fibre hemp (*Cannabis sativa* L.). Field Crops Research Elsevier **40** (3) 153–164.

WILSON K, HANSON P, MULHOLLAND P, BALDOCCHI D AND WULLSCHLEGER S (2001) A comparison of methods for determining forest evapotranspiration and its components: sap-flow, soil water budget, eddy covariance and catchment water balance. Agricultural and Forest Meteorology **106**(2) 153–168.

WIMALASIRI E, JAHANSHIRI E, CHIMONYO V, KURUPPUARACHCHI N, SUHAIRI T, AZAM-ALI S and GREGORY P (2021) A framework for the development of hemp (*Cannabis sativa* L.) as a crop for the future in tropical environments. Industrial Crops and Products Elsevier, **172** 113999.

ZWART S and BASTIAANSSEN W (2004) Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agricultural Water Management **69** 115–133.

CHAPTER 4 WATER USE MEASUREMENTS OF *CANNABIS SATIVA* IN KWA-ZULU NATAL – POT TRIALS

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4.1 KwaZulu-Natal pot trial measurements background

The increasing drought spells are pushing the agricultural sector to consider drought tolerant plants with improved water use efficiency and appropriate physiological responses. This is one of the strategies put into place to ensure primary production while adapting to the current climate change (Gill et al., 2022). Cannabis is one of the crops in question as to its water use efficiency and drought tolerance while maintaining its primary yield. Water is an essential resource for plant growth, most especially during the growth season, and cannabis is no exception (Wartenberg et al., 2021). There is conflicting evidence from studies on the water use efficiency and drought tolerance of *Cannabis sativa*. Hemp performance was not affected by water scarcity and irrigation variations (Amaducci et al., 2015). Herppich et al. (2020) concluded that hemp strains can grow under irregular irrigation in intensively hot and drought conditions. In environments that are hot and arid (high evapotranspiration demand), cannabis has a water consumption ranging from 250-450 mm a^{-1} (Cosentino et al., 2012) but in places of low evapotranspiration it varies between 200-300 mm a^{-1} (Amaducci et.al., 2000). The lack of scientific research has led to the anecdotal knowledge of the cannabis plant in relation to different environmental conditions gathered from small-scale illicit drug farmers (Zheng et al., 2021).

WUE is either measured as instantaneous or intrinsic. Instantaneous water use efficiency (WUEins) is the ratio of the net photosynthetic rate (An) and the transpiration rate, whereas the intrinsic water use efficiency (WUEi) is the ratio of net photosynthetic rate to stomatal conductance (gs). Transpiration is the process through which a plant loses water, mostly through leaf stomata (von Caemmerer and Baker, 2007). The stomatal opening is necessary for CO_2 intake and O_2 release during the photosynthesis process. The availability of adequate environmental conditions is essential as a deficit or an abundance of any results in a change in plant physiological processes. The vegetative stage of the plant necessitates all the physiological activities required for establishment and development, especially photosynthesis. Light, water and CO_2 are the driving factors for photosynthesis. Photosynthesis allows the access of photo assimilates through the source-sink relationship for growth, development, storage, and defence by the plant organs (Brazel and Ó'Maoiléidigh, 2019). In the soil, when the roots absorb water, it is in solution form as it contains nutrients from the soil (Reichardt et al., 2020). Optimal cultivation conditions for *Cannabis sativa* include temperatures between 25-30°C and photosynthetic photon flux densities around 1500 μmol m^{-2} s^{-1} (Chandra et al., 2008). Elevated CO_2 concentrations (750 μmol mol^{-1}) stimulate photosynthesis and WUE while suppressing transpiration and stomatal conductance (Chandra et al., 2008). Potassium nutrition affects plant development, photosynthesis, and water relations, with genotype-specific responses to K supply (Saloner et al., 2019). These findings highlight the complex interactions between environmental factors and cannabis physiology, offering insights for optimizing cultivation practices and water use efficiency. This chapter focused on the effect of different water regimes on the morphological structure, physiological processes and yield of *Cannabis sativa*. The aim was to investigate the water use of *Cannabis sativa* in a pot experiment conducted under greenhouse conditions in the KwaZulu-Natal region of South Africa. The ability of cannabis to produce adequate yield in water scarce conditions was also assessed.

4.2 Study site description and relevant maps

The pot experiment was conducted in a shade house located at the University of KwaZulu-Natal, Agricultural campus in Pietermaritzburg (29°37'33.9"S; 30°24'14.6"E; 670 m a.s.l.). The shade house has a grey net that reflects up to 90% of the sunlight. The Cherry wine (C1) strain seeds were purchased through an online store and the genotype 9 (Lot 9) (C2) is a landrace from Bergville, KwaZulu-Natal. During planting, the seeds were first soaked in water for 2 hours and then placed in seedling trays filled with peat moss. They were later transferred to 10-litre pots and an organic compost mixture for growing media used. The co-compost samples were sent to the Department of Agriculture and Rural Development for analysis. The study used two varieties, namely, cherry wine and Lot 9. The strains were subjected to four different water regimes. They were exposed to a 100% (T1), 90% (T2), 60% (T3) and 30% (T4) of the growing media saturation. This experiment was conducted from the 18th of March 2023 to the 15th of July 2023 (Figure 4-3).

The water use experiment was conducted in Tunnel J. The water use experiment was conducted over two seasons where the first season started on the 31st of May 2024 to the 1st of August 2024 (winter) and the second season experiment 12th of September 2024 to the 29th of November 2024 (spring).

Table 4-1 The nutrient and moisture percentage of the growing media from the Department of Agriculture and Rural Development Soil Science laboratories.

Sample ID	Moisture	N	Ca	Mg	K	Na	Cu	Mn	Fe	Al	P	Zn
	%	%	%	%	%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	%	mg/kg
Co-compost	36.22	1.26	1.30	0.21	0.32	705.5	96.6	817	43382	16579	0.46	296.55

4.3 Measurement Approach

4.3.1 Experimental design and crop establishment

The trial was set up as a 2 by 4 factorial experiment in a randomized block design field layout, consisting of two cannabis cultivars and 4 water regimes. The experiment was replicated 4 times with each replication resulting in 32 plots (treatment combination). There are 32 plots with 6 pots or plants in each plot. The seeds were initially planted on trays with 98 cells, with each cell containing two seeds to increase the germination rate. The planted trays were placed in a greenhouse and irrigated once a day for two weeks. A total of 192, 10 L pots were filled with co-compost containing an 85% green waste composition and 15% sludge. The pots were placed inside a shade house. The growing media in the pots was drenched with water before planting.

The trial was conducted using the Cherry wine variety of *Cannabis sativa*. The seeds were first soaked in water for 2 hours and then placed in seedling trays filled with co-compost. They were later transferred to 10-litre pots and an organic compost mixture for growing media used. The surface of the co-compost around the seedling was sealed with a transparent plastic.

4.3.2 Irrigation

The drip irrigation system was programmed to irrigate three times each day. Early in the morning (7:45), afternoon (11:45), and evening (15:45), for 15 minutes each time. The fertilizer utilized was a 2:1:2(45) NPK (fertilizer group 1) fertilizer which includes microelements, cytokinins, and auxins. A water container was used to make the fertilizing solution. The water container was filled with 200 L of water and combined with 4 kg of fertilizer according to the product's instructions. The plants were fertigated once a week. A 10 L watering can was used to irrigate 8 pots, with at least 33.3 grams of fertilizer used per pot. The drip irrigation provided about 580 ml per irrigation time. The plants that were watered up to 100% of volumetric water content for treatment 1, the plants were watered at 90% volumetric water content for treatment 2, for treatment 3 the plants were watered at 60% volumetric water content and for treatment 4 the plants were watered at 30% volumetric water content. Three weeks following seed sowing, the seedlings were transplanted to the pots. To boost crop establishment, all pots were exposed to the same quantity of water for three weeks. The water content of the growth media was measured using a Hydrosense II, which measured the volumetric water content (%), relative water content (%), water deficit reported in millimetres, and the average period of the water content reflectometer. The treatment combination are as follows: T1C1, T1C2, T2C1, T2C2, T3C1, T3C2, T4C1, T4C2. The water use pot experiment on tunnel J was irrigated equally with 750 ml of water weekly.

4.3.3 Data collection and analysis

A temperature and humidity sensor were stationed inside the tunnel to monitor the environmental condition of the shade house. The morphological measurements were taken using a 2-meter stick in centimetres for plant height and a 30 cm ruler for the longest leaf length. The leaf number, node number and the presence of flowers were monitored.

The physiological measurements will be taken using the LI-6400 XT Portable Photosynthesis System (Licor Bioscience, Inc. Lincoln, Nebraska, USA) integrated with an infrared gas analyser (IRGA) attached to a leaf chamber fluorometer (LCF) (640040B, 2 cm^2 leaf area, Licor Bioscience, Inc. Lincoln, Nebraska, USA). The LI-6400 was used between 11h00-14h00 on sunny and clear skies weather. The physiological measurements included the gaseous exchange parameters namely, the transpiration rate (T), net CO_2 assimilation (A), intercellular CO_2 concentration (Ci), stomatal conductance (gi). The instantaneous water use efficiency (WUEins) will be calculated using the ratio of the net CO_2 assimilation and the transpiration rate (Hatfield and Dold, 2019). The intrinsic water use efficiency (WUEi) was calculated as the ratio of the net CO_2 assimilation and stomatal conductance (Hatfield and Dold, 2019). After 3 months, the seeds, stock, and roots were harvested for wet and dry weight measurements to calculate the root-over-shoot ratio. GenStat® (Version 23, VSN International, UK) was used to statistically analyse data using analysis of variance (ANOVA). At the 5% level of significance, the least significant difference was employed to separate means.

In the water use pot trial (tunnel J), the pots were placed on four scales (weighing lysimeters) connected to loadcells (Figure 4-1). The outputs of the loadcells were collected using a data logger

(CR1000X, Campbell Scientific, Somerset West) every 2 seconds and samples every 5 minutes, hourly and daily. The system was calibrated against known masses and air temperatures. There was some diurnal fluctuation with temperature, but this was negligible when calculating the water used over a 40-day period. The plants experienced cold temperatures and diseases during the first season but were not water stressed.

Morphological data was measured once every week for a period of 10 weeks. Plant height, number of leaves, leaf length and leaf width were collected. The plants were harvested and measured for fresh biomass, bud mass and root mass. The plants were put in the oven over drier for over 72 hours. The plant material was weighed for dry mass. The collected data was analysed using Microsoft Excel.

Figure 4-1 The plant pots with 3 females and 1 male plant placed on the loadcells eight weeks after planting

4.4 Results and Discussion

4.4.1 Drought tolerance trial

4.4.1.1 Growing media moisture content

The soil water content for the different water regimes (T1 (100%) - the control, T2 (90%), T3 (60%) and T4 (30%)) indicate that the soil volumetric water content deviation increased with time (Figure 4-2).

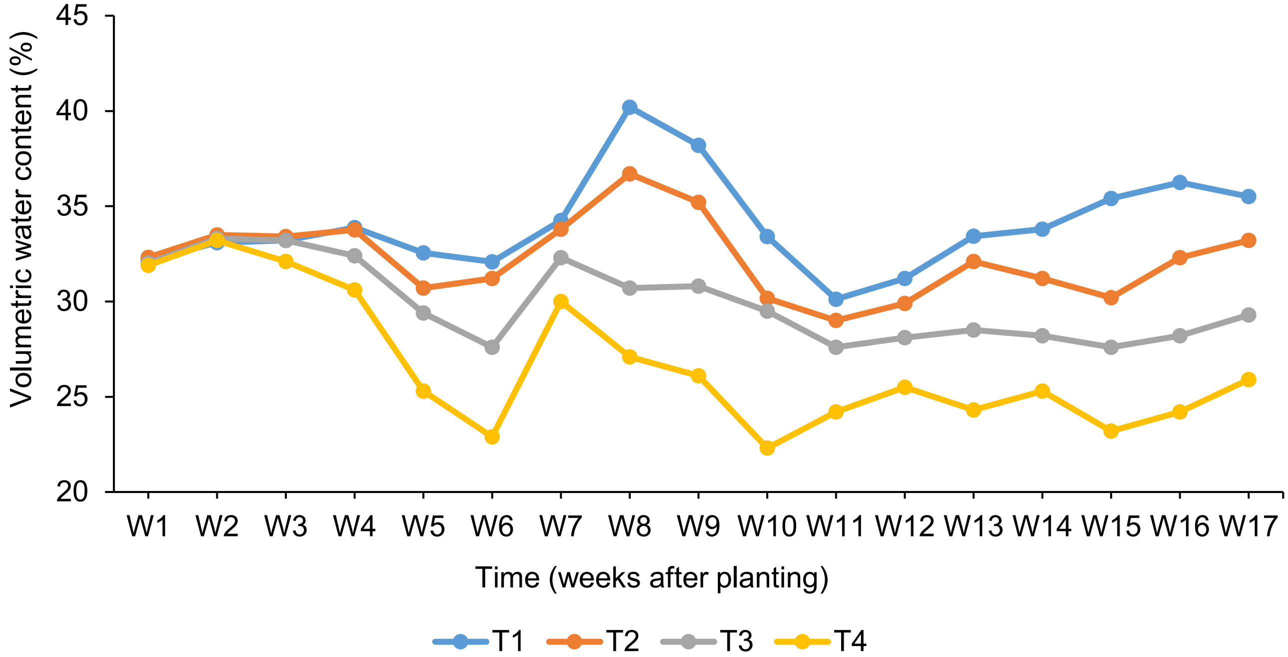

Figure 4-2 The volumetric water content of the growing media observed at a period of 1-17weeks after planting on different water regimes at 100%, 90%, 60% and 30%.

4.4.1.2 Morphology

The pot trial ran for four months and one week. In Table 4.2, the interaction between strain, water regimes, and data collection time is presented. The longest leaf length was significantly affected by strain variation ($p < 0.001$). The varying water regimes had a significant effect on plant height ($p = 0.031$) and on leaf number ($p = 0.002$) (Figure 4-4, Figure 4-5). Data collection time, recorded in weeks, significantly influenced plant height ($p < 0.001$), longest leaf length ($p = 0.003$), number of leaves ($p < 0.001$), and number of nodes ($p < 0.001$). The interaction between strain and water regimes significantly affected plant height ($p = 0.010$) and longest leaf length ($p < 0.001$). However, over time, treatment combinations showed no significant effect on any morphological traits.

Figure 4-3 The illustration of the growth stages of Cannabis sativa L. over time; 3 weeks after transplanting, 4 weeks after transplanting, 6 weeks after transplanting and 7 weeks after transplanting

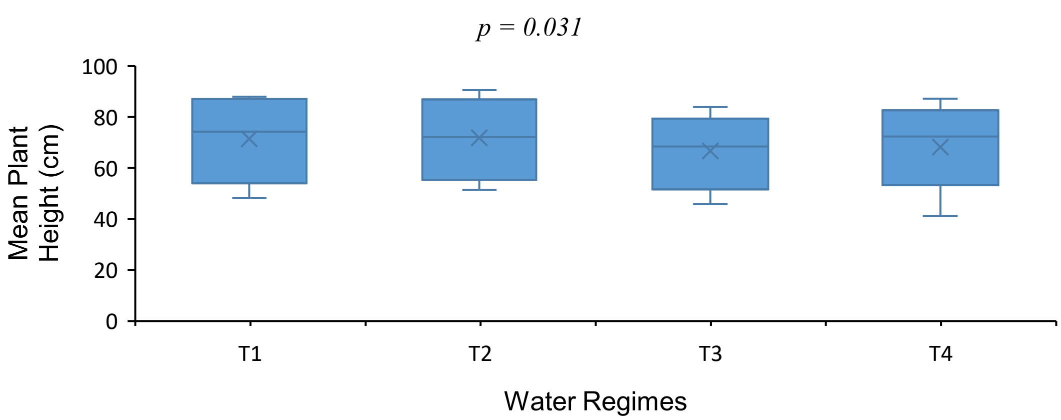

Figure 4-4 The mean plant height in the varying water regimes with a p value of 0.031

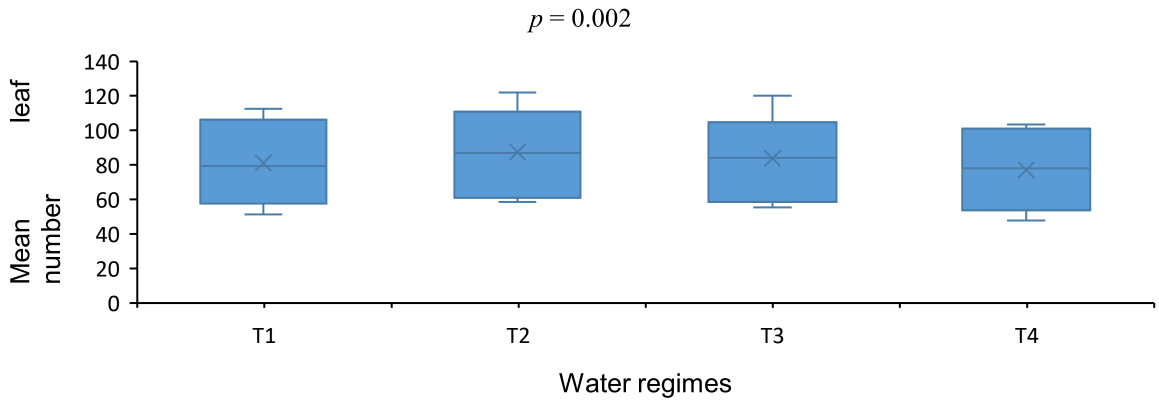

Figure 4-5 The mean number of leaves was significantly affected by the varying water regimes at a p value of 0.002

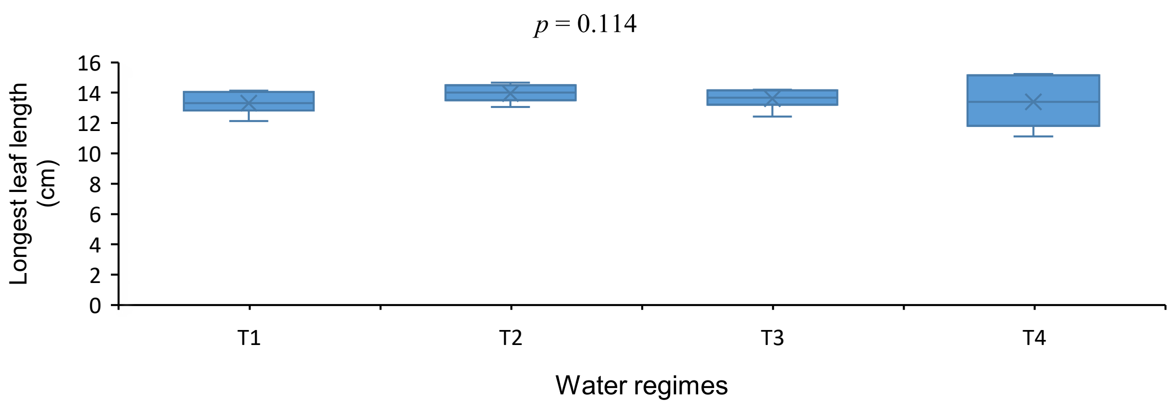

Figure 4-6 The leaf length was not significantly affected by the water regimes with a p > 0.05

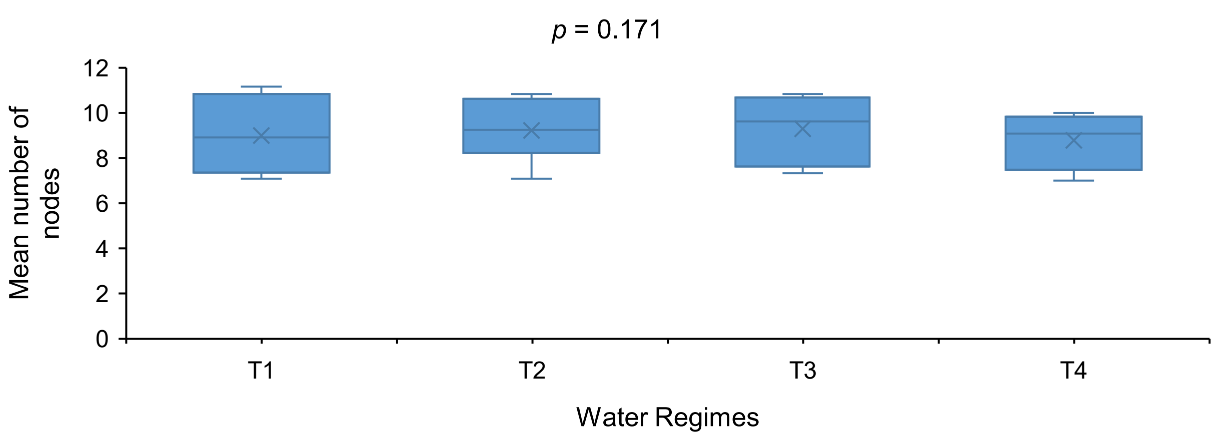

Figure 4-7 The differentiating water regimes did not significantly affect the varying number of nodes

Table 4-2 The mean values of plant height, longest leaf length, number of leaves and nodes of Cannabis sativa strains that are subjected to varying water regimes (treatments)

Treatment	Mean Height (cm)	Treatment	Mean number of leaves	Treatment	Mean longest leaf length (cm)	Treatment	Mean number of nodes
Cherry wine T2 4	90.5a	Lot-9 T2 3	122a	Lot-9 T4 3	15.23a	Lot-9 T1 4	11.167a
Cherry wine T2 3	87.92ab	Cherry wine T3 3	120ab	Lot-9 T4 4	15.18a	Lot-9 T1 3	11.167a
Lot-9 T1 4	87.83ab	Cherry wine T1 4	112.42abc	Lot-9 T4 2	15.02ab	Cherry wine T3 4	10.833a
Cherry wine T1 4	87.75ab	Cherry wine T2 3	110.75abc	Lot-9 T2 4	14.67abc	Cherry wine T2 4	10.833a
Lot-9 T4 4	87.17ab	Cherry wine T2 4	110.75abc	Lot-9 T2 3	14.57abc	Cherry wine T2 3	10.833a
Cherry wine T1 3	84.83ab	Lot-9 T2 4	107.17abc	Lot-9 T4 1	14.36abcd	Cherry wine T3 3	10.75a
Lot-9 T1 3	84.08ab	Lot-9 T1 3	106.67abc	Lot-9 T2 2	14.22abcd	Lot-9 T3 3	10.5ab
Cherry wine T3 4	83.92ab	Cherry wine T3 4	105.67abc	Lot-9 T3 4	14.19abcd	Lot-9 T3 4	10.25ab
Lot-9 T2 4	83.67ab	Lot-9 T1 4	104.42abc	Cherry wine T2 4	14.18abcd	Lot-9 T2 4	10abc
Lot-9 T4 3	83.25ab	Cherry wine T4 3	103.42bc	Cherry wine T3 4	14.18abcd	Cherry wine T4 4	10abc
Cherry wine T4 4	80.42abc	Lot-9 T3 3	101.5c	Lot-9 T1 1	14.13abcd	Lot-9 T2 3	10abc
Cherry wine T3 3	79.75abc	Lot-9 T4 4	101.42c	Lot-9 T1 4	14.13abcd	Cherry wine T1 4	9.833abcd
Lot-9 T2 3	78.08abcd	Lot-9 T3 4	99.83c	Lot-9 T3 3	14.08abcd	Cherry wine T1 3	9.833abcd
Lot-9 T3 4	77.92abcd	Lot-9 T4 3	99.5c	Lot-9 T1 3	13.82abcde	Lot-9 T4 4	9.833abcde
Cherry wine T4 3	76.67abcde	Cherry wine T1 3	99.08c	Cherry wine T2 3	13.82abcde	Cherry wine T4 3	9.833abcdef
Lot-9 T3 3	74.08bcdef	Cherry wine T4 4	94.83c	Cherry wine T3 3	13.81abcde	Lot-9 T4 3	9.75abcdefg
Lot-9 T4 2	67.92cdefg	Lot-9 T3 2	68.42d	Lot-9 T3 1	13.55abcdef	Cherry wine T3 2	9bcdefgh
Lot-9 T2 2	66.08defg	Cherry wine T2 2	66.67de	Lot-9 T2 1	13.53abcdef	Lot-9 T2 1	8.5cdefghi
Cherry wine T2 2	64.42efgh	Cherry wine T2 1	65de	Cherry wine T2 1	13.48abcdef	Cherry wine T2 2	8.417cdefghi
Cherry wine T1 2	64.25efgh	Cherry wine T3 2	62.17de	Cherry wine T1 3	13.41abcdef	Lot-9 T4 2	8.41cdefghi
Lot-9 T1 2	63.5efgh	Lot-9 T4 2	61.33de	Lot-9 T3 2	13.4abcdef	Lot-9 T3 2	8.25defghi

Cherry wine T3 2	62.67fgh	Lot-9 T1 2	59.5de	Cherry wine T1 4	13.22bcdef	Cherry wine T4 2	8.167dghi
Lot-9 T3 2	60.17ghi	Lot-9 T2 1	59.5de	Cherry wine T3 2	13.15bcdef	Lot-9 T2 2	8.167deghi
Cherry wine T4 2	56.33ghij	Lot-9 T2 2	58.5de	Cherry wine T2 2	13.06bcdef	Cherry wine T1 2	8hi
Lot-9 T2 1	52.29hijk	Cherry wine T1 2	57.67de	Cherry wine T1 1	12.83cdefg	Lot-9 T1 2	7.667hi
Lot-9 T4 1	52.08hijk	Lot-9 T1 1	57.58de	Lot-9 T1 2	12.83cdefg	Cherry wine T3 1	7.417hi
Cherry wine T2 1	51.42hijk	Lot-9 T3 1	57.33de	Cherry wine T3 1	12.43defg	Lot-9 T3 1	7.333hi
Lot-9 T1 1	50.83hijk	Cherry wine T3 1	55.33de	Cherry wine T4 4	12.41defg	Cherry wine T1 1	7.25i
Lot-9 T3 1	48.75ijk	Lot-9 T4 1	54.83de	Cherry wine T1 2	12.13efg	Cherry wine T4 1	7.25i
Cherry wine T1 1	48.12ijk	Cherry wine T4 2	53.42de	Cherry wine T4 3	12.03efg	Cherry wine T2 1	7.083i
Cherry wine T3 1	45.82jk	Cherry wine T1 1	51.33de	Cherry wine T4 2	11.74fg	Lot-9 T1 1	7.083i
Cherry wine T4 1	41.17k	Cherry wine T4 1	47.83e	Cherry wine T4 1	11.11g	Lot-9 T4 1	7i

4.4.1.3 Physiology

As the irrigation percentage decreased, it had a notable impact on several physiological processes, including stomatal conductance ($p < .001$), transpiration rate ($p < .001$), and CO_2 assimilation rate per intercellular CO_2 concentration ($p < .001$) (Table 4-3). Significant variations were observed among different strains in terms of stomatal conductance ($p = 0.021$), effective quantum efficiency of PSII photochemistry ($p = 0.011$), electron transport rate ($p = 0.011$), Fo' ($p = 0.027$), Fm' ($p = 0.011$), and relative measure of electron transport to oxygen molecules ($p = 0.004$) (Table 4-3).

The variance in irrigation regimes had a pronounced influence on stomatal conductance, with the highest recorded values observed under the 100% irrigation treatment at 0.558 mmol m^{-2} s^{-1} (Table 4-4). This was followed by the 90% treatment at 0.4758 mmol m^{-2} s^{-1} and the 30% treatment at 0.4626 mmol m^{-2} s^{-1}, respectively. In contrast, the lowest values were observed under the 60% irrigation application, with a stomatal conductance of only 0.4481 mmol m m^{-2} s^{-1}. The stomatal conductance exhibited variability among strains as well, with cherry wine showing the greatest level at 0.5078 mmol m^{-2} s^{-1} and lot-9 displaying the lowest level at 0.4658 mmol m^{-2} s^{-1}. The transpiration rate varied significantly, with the lowest recorded at 60% (10.1 mmol H_2O m^{-2} s^{-1}), followed by 90% (10.68 mmol H_2O m^{-2} s^{-1}) (Table 4-4). In contrast, a higher irrigation percentage of 100% resulted in the highest transpiration rate of (12.14 mmol H2O m^{-2} s^{-1}), followed by 30% at (10.87 mmol H_2O m^{-2} s^{-1}) (Table 4-4). The rate of CO_2 assimilation per intercellular CO_2 concentration is significantly affected by varying levels of irrigation, with 100% irrigation resulting in the highest value of 0.3504 µmol. mol m^{-1} (Table 4-4). This is followed by 90% irrigation at a level of 0.2965 µmol. mol m^{-1}, 60% at 0.2824 µmol. mol m^{-1} and the lowest being observed at 30% with a value of 0.267 µmol. mol m^{-1} (Table 4-4). The CO_2 assimilation rate and intercellular CO_2 concentration of the various strains were significantly influenced by the irrigation regimes. In all irrigation regimes, Cherry wine exhibited the highest levels compared to Lot-9 (Table 4-4).

Table 4-3 The analysis of variance with mean squares and significant tests for leaf gas exchange parameters and the chlorophyll fluorescence parameters for two cannabis strains grown under different water regimes

Leaf gas exchange parameters									
Source of variation	**d.f**	**Gs**	**T**	**A**	**Ci**	**A/Ci**	**Ci/Ca**	**WUEi**	**WUEins**
Irrigation	3	<.001^{s}	<.001^{s}	0.676^{ns}	0.533^{ns}	<.001^{s}	0.155^{ns}	0.493^{ns}	0.736^{ns}
Strain	1	0.021^{s}	0.216^{ns}	0.152^{ns}	0.476^{ns}	0.158^{ns}	0.653^{ns}	0.536^{ns}	0.583^{ns}
Strain x Irrigation	3	0.124^{ns}	0.867^{ns}	0.137^{ns}	0.505^{ns}	0.032^{s}	0.360^{ns}	0.298^{ns}	0.242^{ns}
Residual	565	0.04745	16.46	16.65	22740	0.03017	2523	8633	12.40
Chlorophyll fluorescence parameters									
Source of variation	**d.f**	**Fo’**	**Fm’**	**Fv/Fm**	**ΦPSII**	**qN**	**qP**	**ETR**	**ETR/A**
Irrigation	3	0.907^{ns}	0.826^{ns}	0.351^{ns}	0.115^{ns}	0.459^{ns}	0.464^{ns}	0.104^{ns}	0.077^{ns}
Strain	1	0.027^{s}	0.011^{s}	0.089^{ns}	0.011^{s}	0.079^{ns}	0.234^{ns}	0.011^{s}	0.004^{s}
Strain x Irrigation	3	0.478^{ns}	0.275^{ns}	0.376^{ns}	0.034^{s}	0.337^{ns}	0.315^{ns}	0.026^{s}	0.004^{s}
Residual	565	13302	26742	0.001330	0.0001381	0.0009609	6.601	19260000	13719

d.f: degrees of freedom, gs: stomatal conductance, T: transpiration rate, A: net CO_2 assimilation rate, A/Ci: CO_2 assimilation rate/intercellular CO_2 concentration, Ci: intercellular CO_2 concentration, Ci/Ca, ratio of intercellular and atmospheric CO_2, WUEi: intrinsic water use efficiency, WUEins: instantaneous water-use efficiency, Fv/Fm: maximum quantum efficiency of photosystem II photochemistry, ΦPSII: the effective quantum efficiency of PSII photochemistry, qP: photochemical quenching, qN: non-photochemical quenching, ETR: electron transport rate, ETR/A: relative measure of electron transport to oxygen molecules. s and ns denote significant at 5% probability levels and non-significant, respectively.

Table 4-4 The mean chlorophyll fluorescence parameters and the leaf gaseous exchange parameters exposed to different water regimes

Water regimes	gs	T	A	Ci	A/Ci	Ci/Ca	WUEins	WUEintr	Fo'	Fm'	Fv/Fm	ΦPSII	qP	qN	ETR	ETR/A
100%	0.558b	12.14b	35.85a	154.6a	0.3504a	12.57ab	3.961a	94.6a	2589a	2401a	0.08164a	0.006515	0.3237b	0.9261a	2468a	69.87a
90%	0.4785a	10.68a	35.96a	179.5a	0.2965b	22.03b	4.36a	111a	2589a	2408a	0.07653a	0.003336b	0.0888a	0.9298a	1272b	35.68b
60%	0.4481a	10.1a	36.31a	174.1a	0.2824b	8.93a	4.369a	106.6a	2594a	2419a	0.07496a	0.004961a	0.075a	0.9311a	1832ab	52.12ab
30%	0.4626a	10.87a	36.32a	167.2a	0.267b	13.53ab	4.261a	105.2a	2584a	2407a	0.0749a	0.004004a	0.0483a	0.9312a	1472ab	42.92ab
LSD	0.05042	0.939	0.945	34.91	0.04021	11.63	0.815	21.51	26.7	37.85	0.00844	0.00272	0.595	0.00718	1016	38.34b
CV%	4	5.8	3.3	6.6	11.1	53.1	8.2	6	0.9	1.1	6	6.1	852.8	0.4	7.8	7
p-value	<.001	<.001	0.676	0.533	<.001	0.155	0.736	0.493	0.907	0.826	0.351	0.115	0.024	0.459	0.104	0.077

The different lower-case letters indicate the significant difference among the response of plants to the irrigation applied in different regimes. gs; (mmol m^{-2} s^{-1}), T; (mmol H_2O m^{-2} s^{-1}), A; (μmol CO_2 m^{-2} s^{-1}), A/Ci; (μmol. mol m^{-1}), Ci; (μmol. mol m^{-1}), WUEi; [(μmol (CO2) m^{-2}]; WUEins, (μmol. mol^{-1}), Fv/Fm; (ratio); ΦPSII, the effective quantum efficiency of PSII photochemistry; qP, photochemical quenching; qN, non-photochemical quenching; ETR, (μmol e^{-1} m^{-2} s^{-1}); ETR/A, (μmol e μmol_{-1} CO_2)

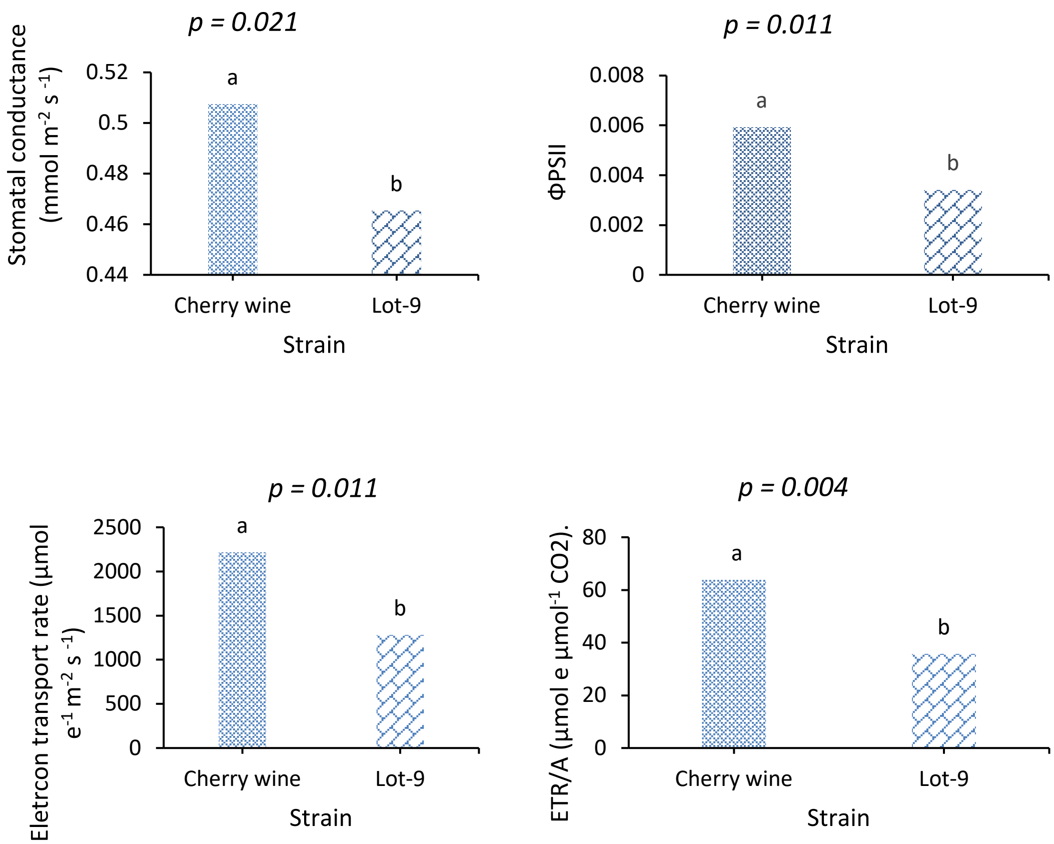

Figure 4-8 The variance in the physiological properties; stomatal conductance, the effective quantum efficiency of PSII photochemistry, electron transport rate and relative measure of electron transport to oxygen molecules of cherry wine and Lot-9

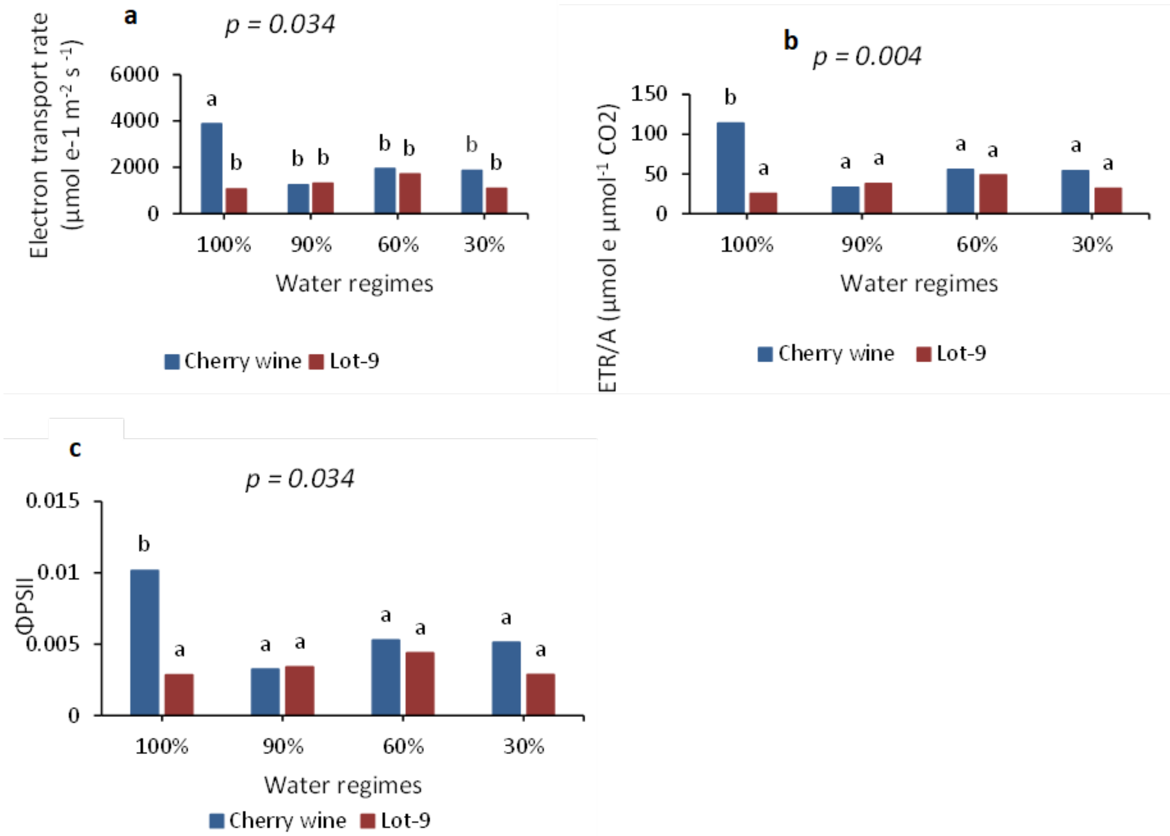

Figure 4-9 The effect of the varying water regimes on the physiological parameters, a) electron transportation rate, b) relative measure of electron transport to oxygen molecules and c) the effective quantum efficiency of PSII photochemistry of cherry wine and Lot-9

4.4.1.4 Yield

The shoot mass was significantly affected by the varying water regimes with p = 0.028, where 100% (12 g) water application had the highest shoot mass, followed by 90% (10.3 g), then 60% at 9.65 g (Table 4-5). The lowest application rate (30%) had the lowest shoot mass at 8.3 g. The tap root length and the overall root length were significantly affected by the different water regimes p = 0.016 and p = 0.007, respectively. The 30% water application had the longest root length at 51.51 cm and second longest leaf length at 42.11 cm. The 90% application rate had the longest taproot length of 44.55 cm and the second longest root length of 48.5 cm. The 100% had the shortest root length (41.49 cm) and the second shortest tap root length at 31.84 cm. Lastly, 60% had the shortest tap root length at 29.84 cm and the second shortest root length of 44.6 cm. The harvest index, seed mass, bud mass and yield index did not vary significantly with the varying water regimes (Table 4-5).

Table 4-5 The mean yield parameter of the cannabis plants exposed to different water regimes.

Water regimes	shoot mass (g)	Root mass (g)	bud mass (g)	seed mass (g)	Bud number	Tap root length (cm)	Root length (cm)	Biomass (g)	HI	Yield index (t/ha)
100%	12b	8.003a	47.24a	61.02a	112a	31.84ab	41.49a	128.3a	47.63a	35.38a
90%	10.3ab	8.693a	56.23a	63.2a	118.4a	44.55c	48.5bc	138.4a	45.17a	42.61a
60%	9.65ab	7.629a	52.09a	54.63a	129.8a	29.84a	44.6ab	124a	42.9a	42.35a
30%	8.34a	7.9a	51.43a	57.01a	123a	42.11bc	51.51c	124.7a	44.98a	43.93a
cv%	16.9	5.4	4.2	1.8	8.8	17.1	4	2.8	0.9	8.1
l.s.d	3.046	3.055	15.38	25.57	36.37	10.34	5.641	37.29	9.46	36.83
p value (0.05)	0.028	0.902	0.689	0.897	0.778	0.016	0.007	0.843	5.4	0.968

Cherry wine (6.74 g) had a noticeable low root mass compared to Lot-9 at 9.38 g, as depicted in Figure 4-10a. The shoot mass also varied with the varying water regimes where Lot-9 at 100% irrigation had the highest shoot mass at 15.34 g and had its lowest at 30% with 7.97 g (Figure 4-10c). In contrast, Cherry wine had its lowest shoot mass at 100% (8.66 g) and its highest shoot mass at 60% (10.82g), which is significantly lower compared to that of Lot-9. Lot-9 had the longest root length of 52.62 cm at 90% and is shortest at 60% (42.9 cm) (Figure 4-10b). Cherry wine had the longest root length of 54.87 cm at 30%, and is shortest at 100% (39.3 cm), and there were significant differences by varying water regimes.

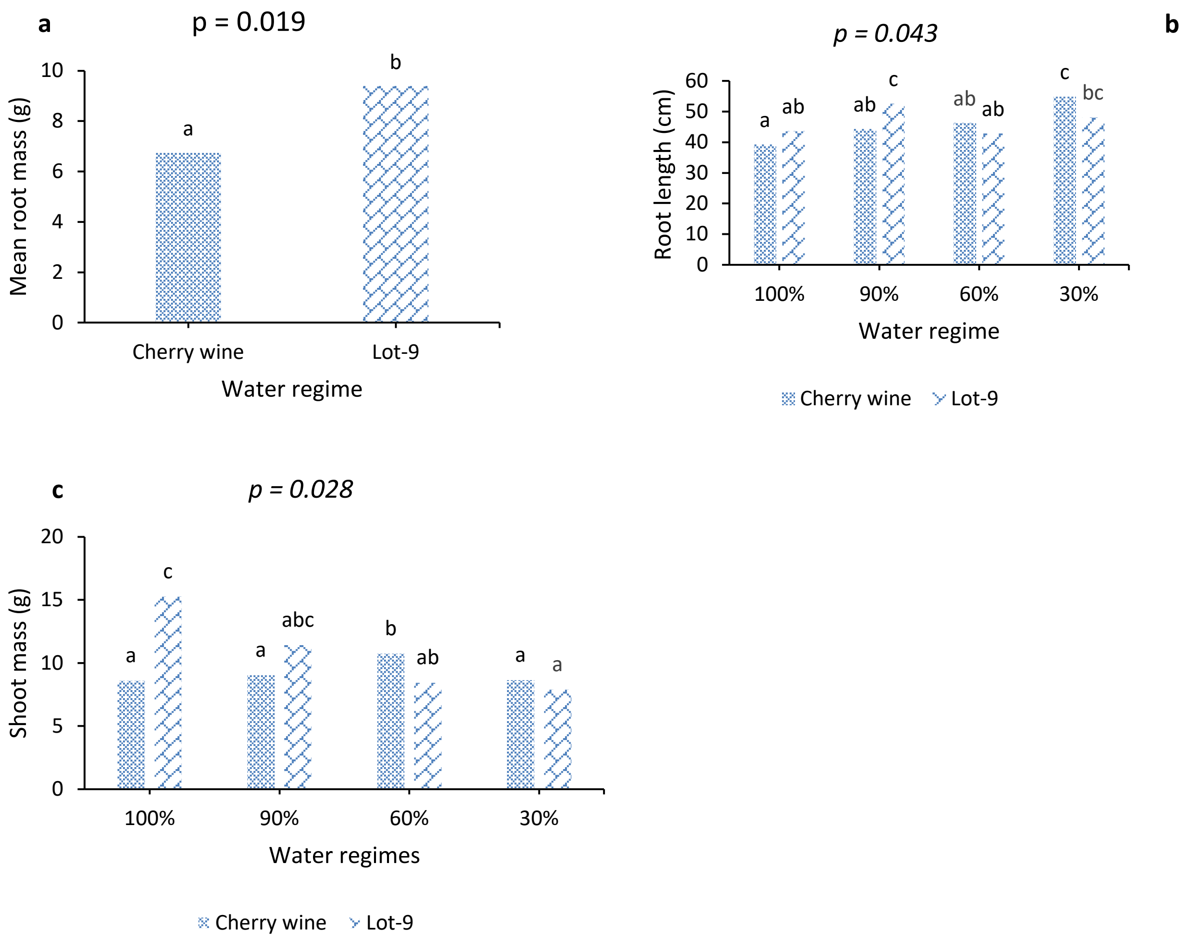

Figure 4-10 The mean yield parameters that were significantly affected by the varying water regimes in relation to the various strains; a) root mass (g), b) root length (cm) and c) shoot mass (g).

4.4.2 Water Use Experiment (Tunnel)

4.4.2.1 Plant height

In the first season of planting, there was a high standard deviation (σ) of 27.4 cm, which suggests a great variation from the mean heights observed for the overall plant height throughout the growing season (Figure 4-11). Plant A had a standard deviation of 20.0 cm, it was 34.9 cm, plant C has a standard deviation of 28.2 cm and for plant D it was 22.9 cm (Figure 4-11).

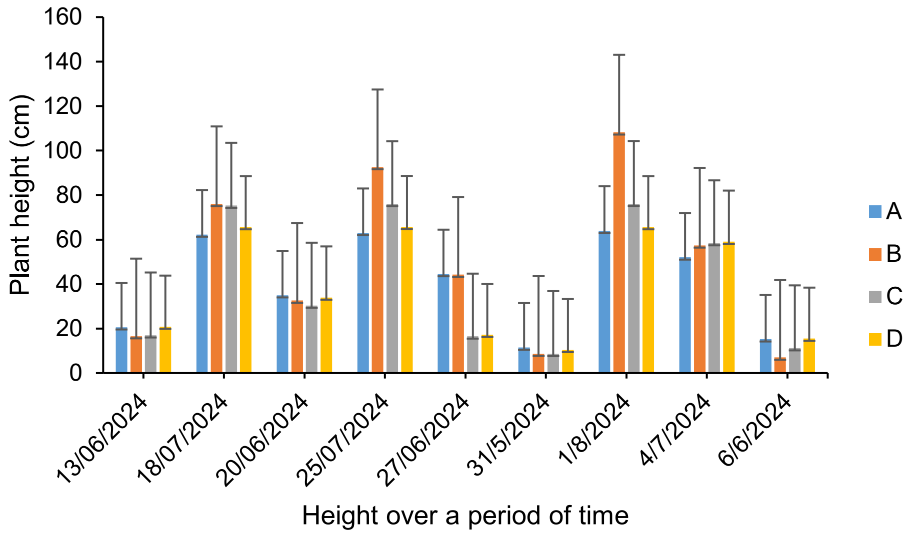

Figure 4-11 Plant height of plants A, B, C and D over the planting period

4.4.2.2 Water use

The change in the mass of the pots was constantly monitored using the weighing lysimeters. In the first season of planting, the plants were exposed to environmental stress conditions including low temperature conditions and photoperiod stress. Plants A, C and D were females and plant B was a male that had no bud yield. The plants utilized an averaged amount of 78 ml day^{-1} over a period of 42 days (18/06/2024-30/07/2024) (Figure 4-12). The second season plants were all female plants that produced bud mass. The plants used an average of 148 ml day^{-1} over a period of 70 days (12/09/2024-29/11/2024) (Figure 4-12).

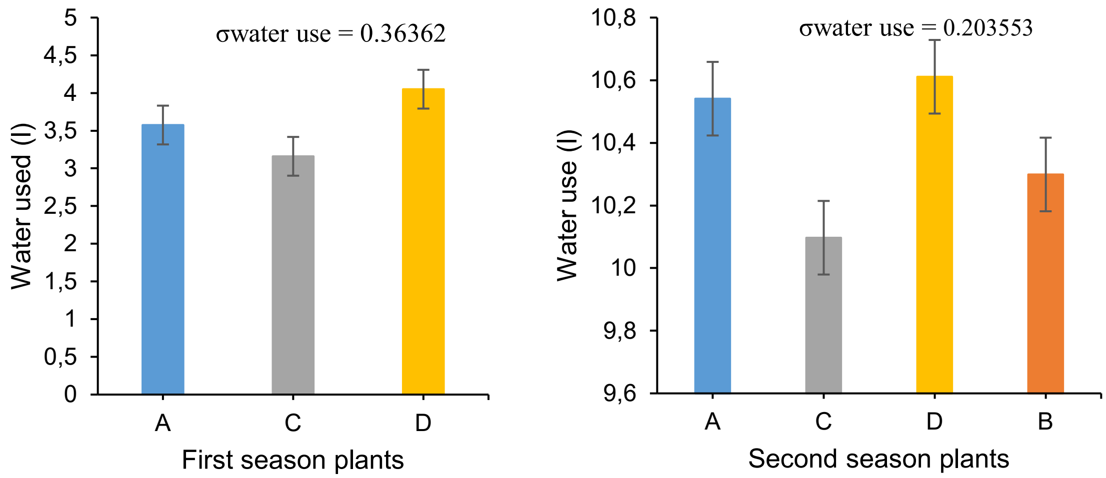

Figure 4-12 The water use of plants over the period of 42 days and 70 days in first season trial and second season trial respectively

4.4.2.3 Water use efficiency

Water Use Efficiency (WUE) is a measure of how efficiently water is used in litres (L) to produce a specific output, such as crop (or bud) yield or biomass in kg. Calculating WUE in kg L^{-1} is done to emphasize the water required to produce crop yield (i.e. the “crop per drop” concept), particularly under water-limited conditions:

$$WUE = \frac{Bud\ mass\ (kg)}{Water\ used\ (L)} \qquad [4\text{-}1]$$

The WUE of Cannabis increased with increasing bud mass. Plant D had the highest bud mass at 0.055 kg (Figure 4-14), and therefore the highest WUE of 0.012 kg L^{-1} (Table 4-6). In the second season, the lowest WUE of 0.005 kg L^{-1} was observed in plant C, where the bud mass was 0.058 kg (Table 4-7). The results show that WUE of Cannabis increased under water (and light) stressed growing conditions.

Table 4-6 Bud mass (kg) per unit of water used (L) by plants over a period of 6 weeks in the first season of planting

Strain	**Water productivity (kg L^{-1})**
Plant A	0.009
Plant C	0.006
Plant D	0.012

Table 4-7 Bud mass (kg) per unit of water used (L) by plants in the second season of planting

Strain	Water productivity (kg L^{-1})
Plant A	0.006
Plant B	0.006
Plant C	0.005
Plant D	0.006

4.4.2.4 Yield data

The plants were harvested after 10 weeks of planting. The yield data was measured for the female plants.

Figure 4-13 Plants harvested from the loadcell experiment

a) Bud mass

The bud mass varied with plants in both the first and the second season. The first season plants had the highest bud mass of 0.055 kg, followed by 0.035 kg and lastly 0.020 kg with the standard deviation of 0.014 kg. These plants had the lowest biomass of 0.090 kg, followed by 0.115 kg and the largest biomass at 0.170 kg, with a standard deviation of 0.033 kg. The standard deviation of both the biomass and the bud mass are low indicating a non-significant variation in the masses. Plants planted in the second season had a biomass and bud mass standard deviation of 0.050 kg and 0.077 kg respectively, showing low variation that is non-significant between the masses. The plants had the highest bud mass of 0.072 kg, followed by 0.065 kg, then 0.064 kg and lastly 0.058 kg. The biomass was lowest at 0.448, followed by 0.564 kg, then 0.591 kg and the highest at 0.660 kg (Figure 4-14).

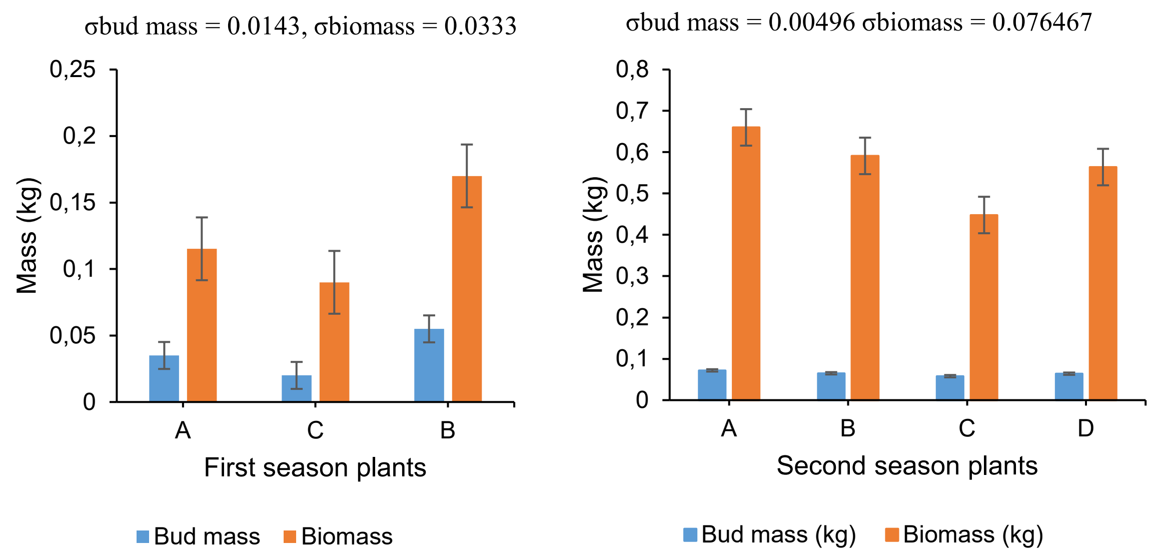

Figure 4-14 The bud mass (kg) and biomass (kg) of plants in the first and second season

b) Water use efficiency and harvest index

The biomass WUE of cherry wine increased with an increase in biomass in both planting seasons. In the first season it ranged from 0.029-0.042 kg L^{-1}, with the standard deviation of 0.0057. The second season plants had a WUE that ranged from 0.044-0.063 kg L^{-1}, with a standard deviation of 0.0067 kg L^{-1} (Figure 4-15).

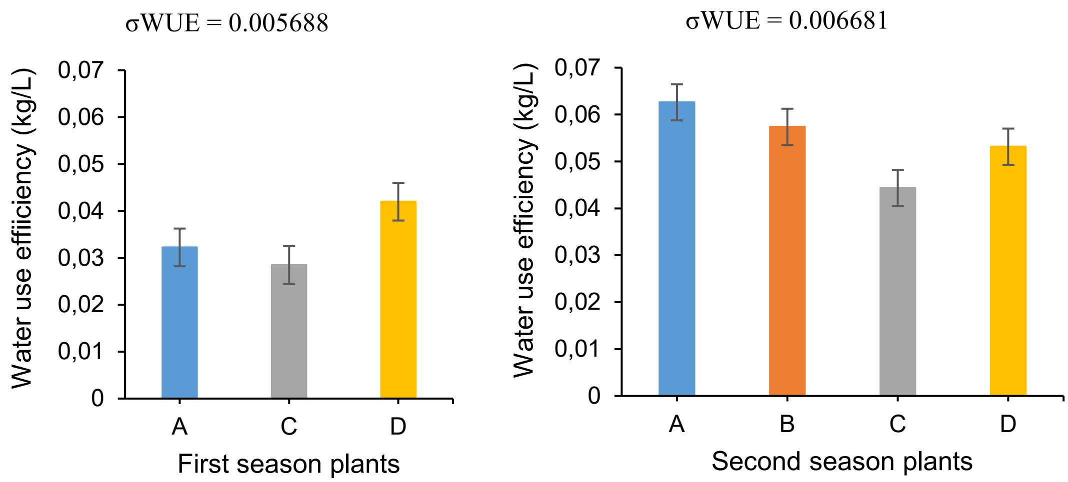

Figure 4-15 The efficiency of plants to produce biomass (in kg) per litre (L) of water used

Harvest index (HI) is the ratio of the economical yield to biomass. HI assesses the effectivity of a plant to allocate water and resources to produce the harvestable portions. Harvest index is calculated as follows:

$$HI = \frac{Bud\ mass\ (kg)}{Biomass\ (kg)} \qquad [4\text{-}2]$$

Plants in the first season had a harvest index ranging from 0.222-0.32 of which is higher that the range of the second season at 0.109-0.129, standard deviation of 0.044 and 0.008 respectively (Figure 4-16).

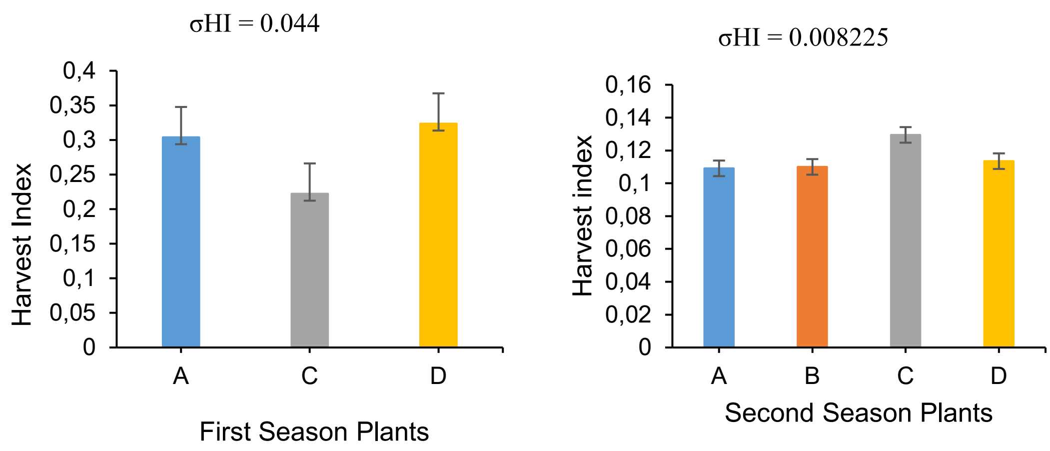

Figure 4-16 The bud mass produced per biomass in kg

c) Root to shoot ratio

Root to shoot ratio is the proportion of a plant's biomass allocated to its roots versus its above-ground parts (shoots, including stems and leaves). It assesses how plants balance water and nutrient uptake (roots) with photosynthesis and growth (shoots). It is calculated as follows:

$$Root{:}Shoot = \frac{root\ biomass\ (kg)}{shoot\ biomass\ (kg)} \quad [4\text{-}3]$$

The first season plants had a root shoot ratio that ranged from 0.438 (highest) to 0.167 (lowest), with a standard deviation of 0.116. The second season root to shoot ration had a lowest 0.559 and its highest at 0.829, with a standard deviation of 0.101 (Figure 4-17).

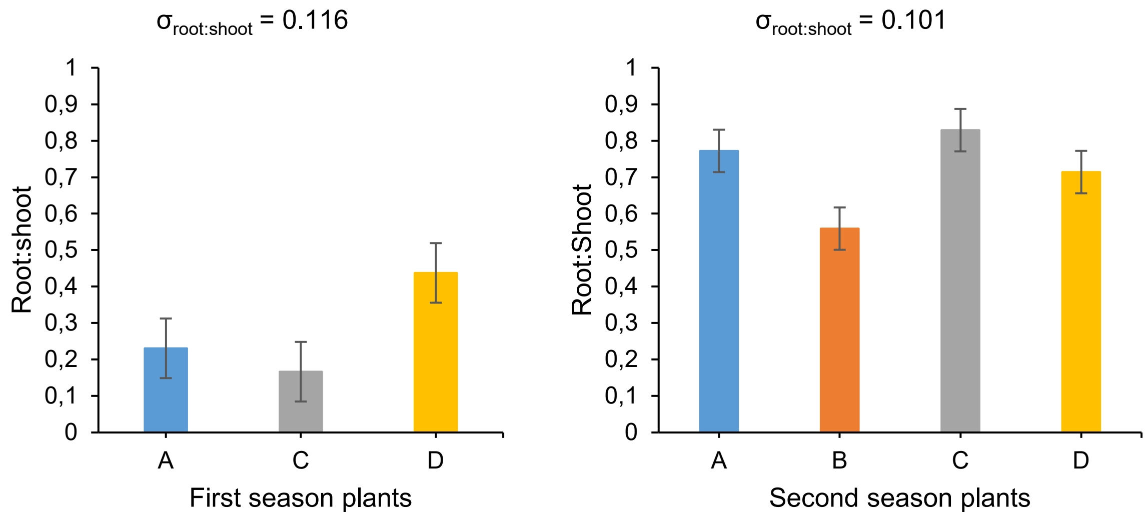

Figure 4-17 Ratio of the plant's root biomass to the shoot biomass

4.5 Discussion

The stomatal conductance and transpiration rate of *Cannabis sativa* significantly declined as water availability decreased. Hence, one of the plant's drought tolerance mechanisms is to regulate stomatal activity to minimize water loss (Morgan et al., 2024). A study done by Morgan et al. (2024) reported a significant reduction in stomatal conductance for both strains in response to drought stress. Cherry wine exhibited a higher CO_2 assimilation rate and electron transport rate ratio compared to Lot-9 in water-stressed conditions. Cherry wine exhibited a better maintenance of the photosynthetic processes despite the low water application of 30% volumetric water content (Morgan et al., 2024). Khatri and Rathore (2019) stated that the net CO_2 assimilation, stomatal conductance, effective quantum efficiency (ΦPSII), intercellular CO_2 concentration and transpiration rate declined significantly under drought and salt stress. Cherry wine exhibited greater indicators of drought-tolerant than Lot-9. The photosynthetic efficiency, as measured by effective quantum efficiency of PSII and electron transport rate revealed a substantial variation between irrigation percentages too, where 100% irrigation rate had much higher values compared to the lower three treatments. A reduction in stomatal conductance at lower irrigation levels did not significantly affect photosynthetic efficiency, suggesting an adaptive mechanism where *Cannabis sativa* can maintain photosynthesis under moderate water deficit (Sheldon et al., 2021).

The plants receiving 100 and 90% irrigation wer significantly higher resulting in significantly greater leaf number compared to the other plants receiving the two lowest irrigation amounts (Figure 4-4, Figure 4-5). The leaf size had no substantial variation indicating that *Cannabis sativa* plant prioritised maintaining leaf function over size under water stress (Tang et al., 2018). The root-to-shoot ratio increased under lower irrigation (30%), indicating a shift in resource allocation where plants invest more in root growth to enhance water uptake. Hemp possesses traits such as deep roots and effective stomatal regulation for drought resistance (Gill et al., 2023). The highest shoot biomass (12 g) was recorded under 100% irrigation, while the lowest (8.34 g) was under 30%

irrigation. The root biomass was not substantially affected by the irrigation levels, but the root length was increased under 30% irrigation level, displaying plant adaptive strategies to enhance water acquisition. Amaducci et al. (2008) observed that while root biomass remained consistent across varying irrigation levels, root length increased under water stressed conditions. This suggests that the plant extends its root system deeper into the soil to access moisture, thereby enhancing its drought resilience. Tang et al. (2018) found that under prolonged water stress, *Cannabis sativa* maintained its root biomass but exhibited increased root length density. This adaptation allows the plant to explore a larger soil volume for water uptake, compensating for reduced water availability in the upper soil layers. Bud yields did not significantly vary among treatments, indicating that *Cannabis sativa* prioritized reproductive growth even under moderate water deficit. The plant allocated more of its resources to the reproductive stage more that the vegetative growth where it had the lowest plant height and number of leaves but maintaining the photosynthetic activities with the plant and regulating water loss through limiting stomal closure and less transpiration rate. Furthermore, the plants exposed to low water irrigation level had the longest root length allowing adapting to moderate water deficit conditions. Water deficit stress generally reduces dry matter production, but some ecotypes show higher WUE and yield under stress conditions (Babaei and Ajdanian, 2020). Plants exposed to lower water availability (30%) exhibited higher water productivity, indicating an improved intrinsic WUE but it was not significantly affected by the water levels and the difference in strains. However, a higher WUE_i indicates that a plant can assimilate more CO_2 per unit of water lost, enhancing its efficiency under low water availability. This improvement in WUE_i often results from a reduction in stomatal conductance while maintaining stable photosynthetic rates. By partially closing their stomata, plants decrease water loss through transpiration, which leads to an increase in WUE_i. This adaptive mechanism allows plants to conserve water during periods of limited availability without significantly compromising carbon assimilation (Ma et al., 2023).

In thje first season, the weighing lysimeter experiment showed the plants used an average of 78 ml day^{-1} whilst experiencing environmental stress factors such as low temperatures and short photoperiods. In the second season, water consumption increased to 148 ml day^{-1}, correlating with improved environmental conditions and plant growth. The variability in water uptake due to the difference in the environmental conditions and plant development stages. The most efficient plant (Plant D) demonstrated a WUE of 0.012 kg L^{-1}, while the least efficient (Plant C) produced 0.006 172.56 kg per litre of wate consumed. WUE values were realtively low in the second season and ranged from 0.005 to 0.006 kg L^{-1}, due to higher water consumption. These variations show Cannabis is moore WUE under stressed conditions, as reproted in the literature. The second season plants had a lower range for WUE compared to the first season data but there was no significant difference between the two seasons' WUE.

The biomass varied in seasons, where in the first season, it ranged from 0.09-0.17 kg and in the second season, it ranged from 0.45-0.66 kg. The plants in the second season were exposed to temperature conditions ranging from a minimum temperature of 15.5˚C to a maximum temperature of 25.0˚C, comapred to the first season, where it ranged from a minimum of 10.5˚C to a maximum of 23.2˚C. The plants were also exposed to shortened photoperiod hours. Daily Light Integral (DLI) significantly affects leaf photosynthesis and WUE under varying light conditions (Saloner et al., 2019). The plants accumulated the highest bud mass of 0.055 kg in the first season and a bud mass of 0.072 kg in the second season. The harvest index exhibited in the first season was higher than that of the second season, indicating that the biomass consists of a larger desired yield compared to the second seasons plant. The root shoot ratio for the first season had lower values indicating stress adaptation and second season plants had a higher value indication investment of the resources on the roots. *Cannabis sativa* has consistently exhibited different drought tolerance traits. Furthermore, the water use study portrays how it efficiently allocated its resources on reproductive growth more than that of vegetative growth. However, it produced the desired harvestable mass of which did not vary much from the second season plants that were exposed to adequate growing conditions.

4.6 Conclusion

Cannabis sativa demonstrated the ability to adapt to drought or water deficit conditions. Where it exhibited drought tolerance indices such as stomatal regulation and decreasing transpiration rate, it did so whilst maintaining photosynthetic activity. The plants exposed to low water levels and environmental stresses invested more photo assimilates on reproductive growth and limited vegetative growth and grew root length to access water deeper within the growing media. This study contributed towards identifying *Cannabis sativa* as a plant that can survive in moderate water deficit conditions. Further studies should explore long-term drought adaptation and nutrient interactions to refine these findings for commercial application.

4.7 References

AMADUCCI S, SCORDIA D, LIU FH, ZHANG, Q, GUO, H, TESTA, G. AND COSENTINO, S.L, 2015. 2015. Key cultivation techniques for hemp in Europe and China. Industrial Crops and Products **68** 2-16.

AMADUCCI, S, ZATTA, A, PELATTI, F. AND VENTURI, G, 2000. Influence of agronomic factors on yield and quality of hemp (*Cannabis sativa* L.) fibre and implication for an innovative production system. Field Crops Research **107**(2) 161-169.

AMADUCCI, S, AMADUCCI, M.T, BENATI, R. AND VENTURI, G, 2000. Crop yield and quality parameters of four annual fibre crops (hemp, kenaf, maize and sorghum) in the North of Italy. Industrial Crops and Products **11**(2-3) 179-186.

BUNDWINI, N, 2021. Destigmatise SA's multibillion-rand cannabis sector to achieve, Cape Town: UCT Communication and Marketing Department.

COSENTINO, S.L, TESTA, G, SCORDIA, D. AND COPANI, V, 2012. Sowing time and prediction of flowering of different hemp (*Cannabis sativa* L.) genotypes in southern Europe. Industrial Crops and Products **37**(1) 20-33.

COSENTINO, S.L, TESTA, G, SCORDIA, D. AND COPANI, V, 2012. Sowing time and prediction of flowering of different hemp (*Cannabis sativa* L.) genotypes in southern Europe. Industrial Crops and products **37**(1) 20-33.

GARNIER, E, SHIPLEY, B, ROUMET, C. AND LAURENT, G, 2001. A standardized protocol for the determination of specific leaf area and leaf dry matter content. Functional Ecology 688-695.

GILL, A.R, LOVEYS, B.R, COWLEY, J.M, HALL, T, CAVAGNARO, T.R. AND BURTON, R.A, 2022. Physiological and morphological responses of industrial hemp (*Cannabis sativa* L.) to water deficit. Industrial Crops & Products **187**, p. 115331.

GILL, A.R, LOVEYS, B.R, CAVAGNARO, T.R. AND BURTON, R.A, 2023. The potential of industrial hemp (*Cannabis sativa* L.) as an emerging drought resistant fibre crop. Plant and Soil **493**(1) 7-16.

GOOGLE, n.d. Google Maps: University of KwaZulu-Natal, Carbis Road. [Online] Available at: https://www.google.com/maps/search/University+of+KwaZulu-Natal+carbis+road/@-29.6269107,30.4029604,166m/data=!3m1!1e3?hl=en-ZA&entry=ttu&g_ep=EgoyMDI1MDEwOC4wIKXMDSoASAFQAw%3D%3D [Accessed 14 January 2025].

HATFIELD AND DOLD, J. C, 2019. Water-use efficiency: advances and challenges in a changing climate. Frontiers in Plant Science **10**, p. 103.

HERPPICH, W.B, GUSOVIUS, H.J, FLEMMING, I. AND DRASTIG, K, 2020. Effects of Drought and Heat on Photosynthetic Performance, Water Use and Yield of Two Selected Fiber Hemp Cultivars at a Poor-Soil Site in Brandenburg (Germany). Agronomy **10**(9), p. 1361.

MANU, E, DOUGLAS, M, NTSABA, M.J. AND TARKANG, E.E, 2021. Perspectives of illicit marijuana growers and traders on commercial legalisation of marijuana in South Africa: considerations for policy formulation. Substance Abuse Treatment, Prevention, and Policy **16** 1-13.

WARTENBERG, A.C, HOLDEN, P.A, BODWITCH, H, PARKER-SHAMES, P, NOVOTNY, T, HARMON, T.C, HART, S.C, BEUTEL, M, GILMORE, M, HOH, E. AND BUTSIC, V. 2021. Cannabis and the Environment: What Science Tells Us and What We Still Need to Know. Environmental Science & Technology Letters **8** 98-107.

ZHENG, Z, FIDDES, K. AND YANG, L, 2021. A narrative review on environmental impacts of cannabis cultivation. Journal of Cannabis Research **3**(35) 1-10.

CHAPTER 5 WATER USE MEASUREMENTS OF *CANNABIS SATIVA* IN THE EASTERN CAPE

Authors: Kamva Zenani, Kathleen Smart and Anthony Palmer

5.1 Rationale for the research

There are multiple factors that affect the rate of evapotranspiration, chief amongst them is energy availability in the form of radiation, temperature, humidity, wind speed, land management practices and the physical properties of vegetation such the height, leaf area index, the shape of the leaf and its reflectivity (Stancalie and Nertan, 2012). All these factors play a significant role in the rate of evapotranspiration.

Energy availability in the form of radiation and air temperature are the main driver of evapotranspiration. An increase in temperature increases the rate of evaporation, this is due to the fact that more water molecules in the plant get excited and get enough energy to move to the gaseous phase if temperature is high (Troung, 2012; United States Geological Survey [USGS], 2012). This causes the plant to open the stoma and thus releasing more water into the atmosphere. Lower temperatures have the reverse effect, that is why the summer months experience the highest rates of evapotranspiration. Wind speed is another factor that plays an important role in evapotranspiration, an increase in wind speed results in an increase in evapotranspiration this is because higher wind speeds encourage the movement of saturated air thus allowing much drier air to be available for evapotranspiration (USGS, 2012). The Firglen study site is situated in a valley between two hills and in the summer months it experiences katabatic winds also known as bergwinds, this leads to increased evapotranspiration rates than normal. Relative humidity is different from the other parameters because its increase leads to lower evapotranspiration rates, because higher humidity means the air is saturated with water and therefore there is no space for the evaporating water from the plant thus leading to lower evapotranspiration rates (USGS, 2012). Physical properties also encourage evapotranspiration, plants with leaves that have large surface areas have increased evapotranspiration when compared to plants with smaller leaves (Troung, 2012; USGS, 2012).

5.1.1 Aims

To investigate and better understand the water use of *Cannabis sativa* to make informed decisions about its cultivation under commercialized dryland conditions in south-eastern regions of South Africa.

5.1.2 Objectives

- To plant a crop of *Cannabis sativa* under dryland conditions that will mimic the type of agronomic practices that legacy farmers in the Eastern Cape and KZN could apply.
- Measure the rate of evapotranspiration from a cover of *C. sativa* using a large aperture scintillometer in a dryland location.

- To parameterize and validate a transpiration model (MEDRUSH) that can be used to simulate water use at other sites.
- To measure stomatal conductance under a range of growth and environmental conditions
- To measure leaf stomatal conductance of a range of growth forms of landrace varieties of *C. sativa* throughout its life cycle under dryland conditions
- To measure leaf stomatal conductance of a commercial, high tetrahydrocannabinol (THC) variety of *C. sativa* (Exodus cheese) under tunnel grown conditions.
- To compare and discuss these results in the context of commercializing *Cannabis* production in the region.

The study is based in a dryland location in order to have a similar environment as legacy farmers in the Eastern Cape. In the dryland experiment, landrace cannabis types will be sourced from both the Eastern Cape and in KwaZulu Natal Province. A Large Aperture Scintillometer (LAS) will be used to measure the change in the refractive index of the atmosphere, and it will also be fitted with ancillary instruments to measure meteorological parameters including wind speed, pressure and temperature (Kipp and Zonen, 2021). This will enable us to determine the prevailing weather conditions in real time and the rate of evapotranspiration (ET) from the cannabis.

5.2 Materials and Methods: Site description of dryland trial, Firglen farm, Makhanda

The study site is located on a farm which in turn is situated in a valley about 21 km from Grahamstown/ Makhanda CBD (33°19’10’’ S 26°23’11’’E) Eastern Cape, South Africa (Google Earth, 2021). The area that was cultivated is approximately six metres in width and about 450 m in length. The slope of the area is facing towards the south west direction (Figure 5-1). The area shown below was previously used for cultivation a few decades earlier and therefore it is already cleared with few shrubs and grass remaining.

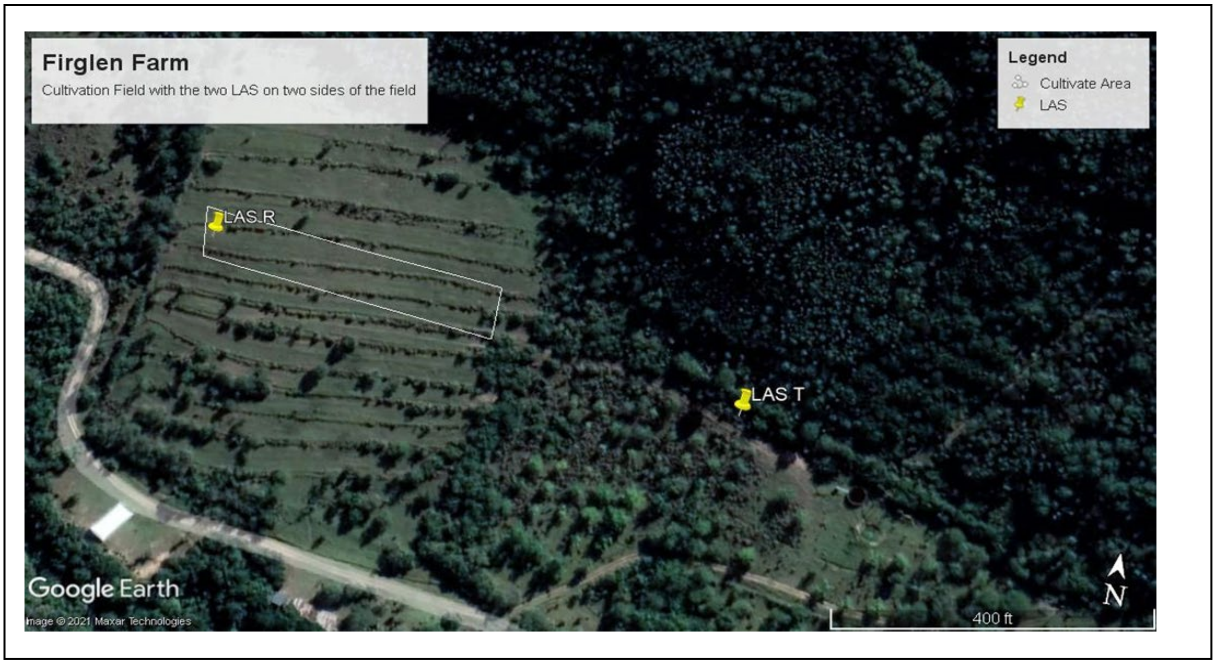

Figure 5-1 Illustrating the study site with the LAS installation. All woody vegetation below the beam of the LAS was cleared.

5.2.1 Climate

The climate of the area is semi-arid, characterised by cold winters and hot summers with a temperature ranging from 0˚C and 40˚C (De Lacy and Shackleton, 2017). The average rainfall at Grant Street, Grahamstown is 650 mm (McConnachie et al., 2008; Palmer, pers. comm, 2022; Figure 5-2) reported a figure 670 mm. The figure below indicates the annual rainfall for Grahamstown from the late 19th century to the year 2012. The two weather stations show different amounts of rainfall throughout the years, this can be attributed to various factors and chief amongst those factors is altitude. The graph shows that there is no clear pattern of rainfall, some years receive more rain than others. The rainfall amounts range from as low as 220 mm to as high as 1000 mm a year.

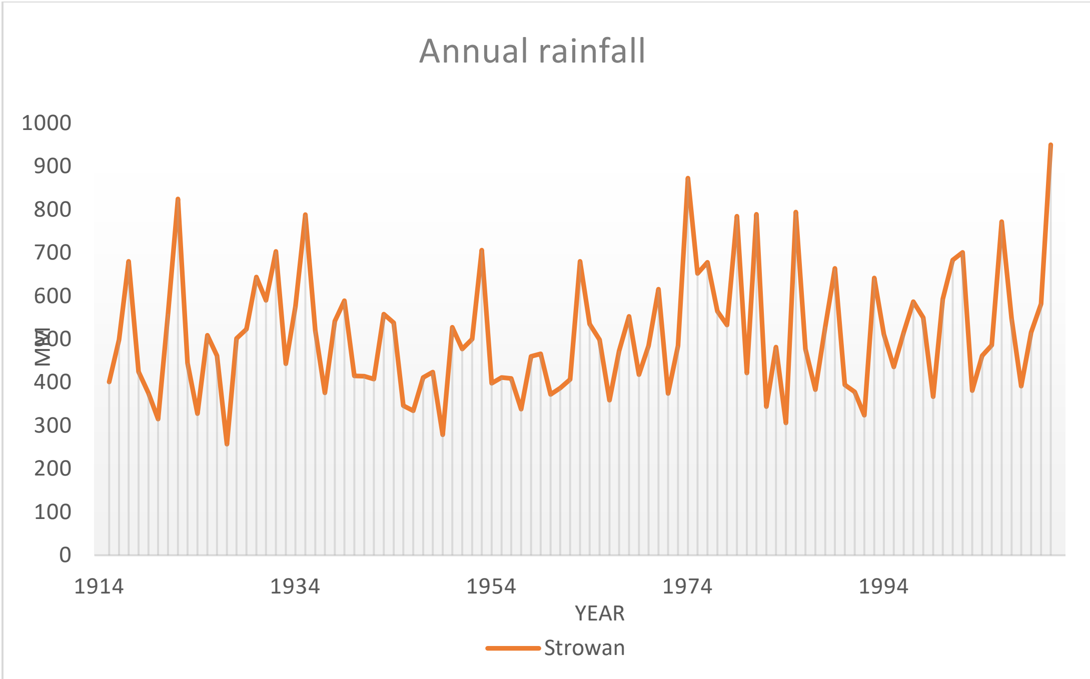

Figure 5-2 Annual rainfall for the farm Strowan, located approximately 14 km east of Firglen

5.2.2 Vegetation

All vegetation follows Hoare et al. (2006) nomenclature. Grahamstown is situated in the Subtropical Thicket Biome of South Africa which consists of 14 vegetation units which include the Sundays Thicket, Coega Bontveld, Sundays Noorsveld, Great Fish Thicket, Kowie Thicket, Great Fish Noorsveld and Southern Mistbelt (Hoare et al., 2006). The vegetation units that are found in Grahamstown include the Great Fish Noorsveld characterised by a diverse vegetation formation such as *Portulacaria afra, Gymnosporia, Schotia, Crassula, Euphorbia bothae*, *Strelitzia reginae* and grasses such as *Eragrostis plana* (Hoare et al., 2006). The Southern Mistbelt Forest vegetation unit can also be found in the high-altitude areas of Grahamstown at about 850m- 1600 m above sea level. This vegetation type is characterised by tall and short trees, *Afrocarpus falcatus, Celtis africana* and *Olea capensis* can be found in this vegetation unit (Hoare et al., 2006). The study area and adjacent farms contain both livestock and numerous game, including baboons (*Papio ursinus*), leopards (*Panthera pardus pardus*), and kudu (*Tragelaphus strepsiceros*), amongst others.

5.2.3 Geology

The geology of Grahamstown is characterised by the occurrence of rocks from both the Cape Supergroup and Karoo Supergroup (Buttner et al., 2015). The Cape Supergroup was deposited during the Ordovician era about 500 million years ago (Evans, 1999). It stretches from the Western Cape to the Eastern Cape Province of South Africa (Lock, 1974; Buttner et al., 2015). The rock formations in Grahamstown belong to both the Witteberg and Bokkeveld group of the Cape Supergroup (Lock, 1974). Most of the Bokkeveld rock formations are found towards the town of Alexandria only a few outcrops around the Makhanda area (Buttner et al., 2015). Grahamstown region is dominated by rocks of the Witteberg Group (Lock, 1974). The Witteberg Group was deposited in a coastal marine setting during the mid-Devonian to mid-Carboniferous era and it is characterised by the occurrence of quartzite with interbedded shales (Buttner et al., 2015). The Witteberg Group is overlain by the glacial deposits of the Dwyka Group of the Karoo Supergroup (Lock, 1974). The Dwyka Tillite is in turn overlain by the Ecca Group. These two groups are only exposed in the northeast of Grahamstown (Lock, 1974). The Dwyka is dominated by glacial till while the Ecca group is dominated by sandstone and shales (Buttner et al., 2015).

5.2.4 Soil

Soil samples were collected from nearby, approximately 500m east of our study site, the area is a comparable abandoned field. All organic material in the top 3cm was removed. A hand-held, bucket-type soil auger was used to collect approximately 500g of a mixed sample from the top 30cm. Samples were oven-dried and sent to Dohne Soil Laboratory in Stutterheim for analysis. Samples were analysed for phosphorus, potassium, calcium, magnesium, exchange acidity, total cations, pH, zinc, manganese, and copper. The samples were collected from mounds/contours and off mounds. The soils in Firglen are nutrient deficient with most of the macronutrients significantly depleted, this is especially the case on off-mounds where the nutrient levels are very low. The on-mound nutrient levels were higher when compared to the off-mound. The soils are also acidic exhibiting a pH below five. The soil type of the area varies from location to location, but the predominant types are sandy loam and clay loam.

5.2.5 Land use

Historically the Makhanda area and Firglen were occupied by Xhosa pastoralists and San hunter-gatherers for centuries who used this area primarily for grazing their cattle and hunting until the arrival of European settlers in the 1920s (South African History Online [SAHO], 2023). The arrival of Europeans changed the way the land was utilised since the Europeans came with new farming methods (SAHO, 2023). The largely dense thicket was cleared to make way for cultivation and grazing for cattle (SAHO, 2023). Firglen has been cultivated for decades but cultivation has since ceased in the area. According to a local farmer Du Preez (2023), the area was cultivated with tomatoes and flowers and small stock farming was practiced evidenced by the occurrence of water troughs. The cultivation practices of the past have left the soils at Firglen nutrient-deficient and acidic even though the area has not been cultivated in over 50 years. This further illustrates the importance of good land management and cultivation practices. The predominant land use today is grazing for Nguni cattle for a few months of the year. The farmer practices rotational grazing to curb overgrazing that might lead to a plethora of environmental problems such as biodiversity decline, reduced biomass and land degradation. According to Snyman (1999) in degraded landscapes, water is utilised inefficiently regardless of the amount of water that is available. Therefore, degraded landscapes pose a serious problem in the cultivation of *C. sativa* since these landscapes will not be able to utilise water efficiently for the benefit of the plants. The farm is also a home to various herbivores such as kudu (*Tragelaphus strepsiceros*).

5.3 Experimental design and layout at Firglen

5.3.1 Germination

Germination was undertaken using landrace seeds and followed a recognised procedure. Phase one the seeds are germinated on trays for approximately four weeks. The seeds are immersed or soaked in different jars of water for 24 hours, the seeds must sink to the bottom of each container. After 24 hours the seeds must be placed between a double folded paper towel, damp and cover with cling wrap. The next step is to germinate the seeds that have roots in trays that are filled with a mixture of cannabis soil mixture, potting soil, powder feeding and vermiculite (magnesium-aluminium-iron silicate). Vermiculite has properties that allow it to absorb significant amount of water and attract other minerals that are essential for plant growth such as potassium. The seeds must be planted to a depth of about two centimetres. Upon completion of germination, a total of about 450 *Cannabis sativa* seedlings with a distance between them on the trays of approximately 30cm. The plants need to be watered twice daily in the morning and afternoon at for 10 to 15 minutes using a hose pipe connected to a tap near the nursery facility at Firglen.

5.3.2 Transplanting

When the seedlings are between 15 and 20cm they are transplanted to black two litre plastic bags for hardening. The bags are filled with the same mixture as the one used for the seeds. When the seedlings have an average height of about 35cm they are planted in the cropping area were the Large Aperture Scintillometer and micro-meteorological station are installed. The planting process is carried out by a team of five individuals. A soil auger is used to dig up holes on the ground, the holes have an average depth of 10cm. A total of 450 holes must be dug and the plants are placed in the holes. The spacing between the plants was approximately 40 cm. A drip irrigation system with a tank is installed, this aids in the watering of plants during extreme dry periods and when soil moisture drops below 23%. When it is very dry the plants are watered twice a day for about two hours each using the drip irrigation system. The plants are planted underneath drip irrigation pipes that are placed in a horizontal position, these pipes have about four drip holes and underneath each hole there is a seedling planted. The entire study area is fenced with an electric wire to protect the crop from herbivory. At the Sweetwater's facility in Kenton-on-Sea the plants planted in the soil received about 4 litres of water an hour (see Appendix D for details of the design and layout) and literature also suggest that the plant needs substantial amounts of water for example Cosentino et al. (2012) recommends 450 mm of water for *C. sativa* growing semi-arid areas. The research team has suggested watering in the morning around nine for two hours then again in the afternoon around two for another two hours. There the plants are watered for two hours in the morning and another two hours in the afternoon. Planting on the field commenced on the first week of November 2022.

5.3.3 Biophysical monitoring

The main aim of biophysical monitoring at the Firglen study site is to monitor the progress of the plants throughout the growing cycle. This includes monitoring the pH of the soil, the air and soil temperature, soil moisture, measure the leaf are index, the amount of photosynthetically active radiation, height and width of the plant and stomatal conductance. We also monitor the amount of water that is used for irrigation purposes.

5.4 Instruments

5.4.1 Introduction

At Firglen, water was determined by triangulation using modelling, and two forms of direct measurement. The first two direct methods include the use of a large aperture scintillometer (LAS MkII, Kipp and Zonen, Netherlands, 2022) and a hand-held SC-1 model leaf porometer to measure stomatal conductance (Decagon Devices, US/ Canada). The third method involves the use of the MEDRUSH transpiration model (Osborne and Woodward 1999) (University of Sheffield, United Kingdom), and it is particularly appropriate for crops in Mediterranean-type climates.

5.4.2 Large Aperture Scintillometer (LAS)

A Large Aperture Scintillometer (LAS MkII, Kipp and Zonen, 2022) was installed on the study site at Firglen on the first of October 2021. A LAS measures the refractive index of air (C_n^2) over horizontal path lengths from 250 m to 4.5 km 0.149 m diameter (D) beam (Campbell Scientific). This instrument uses the principle of scintillation to obtain measurements (Hemakumara et al., 2003). Refractive index fluctuations are due to distortion of a wave traveling through air (Hemakumara et al., 2003). Hemakumara et al. (2003) describes scintillation as changes in the brightness of an object when viewed in the earth's atmosphere. The measured refractive index fluctuations are used to determine sensible heat flux. The data logger for the LAS MkII is a combilog data logger 1022 with an operating temperature between 20˚C and 60˚C (LAS MkII, Kipp and Zonen, 2022). The collected data is uploaded on the Evation software (LAS MkII, Kipp and Zonen, 2022) and it is used for obtaining relative humidity, evapotranspiration and radiation. The software will also generate graphs that depict the interaction between ET, Radiation and Relative humidity. LAS consists of a transmitter and receiver which are situated on opposite ends of the study area. The light transmitted by the LAS MkII transmitter emits a light that is near infrared at wavelength of 850 nanometre (Palmer et al., 2022). The LAS and the micro meteorological station are connected to the internet and all the collected data can be accessed remotely. The study site in Firglen was chosen due to its suitability to host LAS, there is relatively homogenous vegetation consisting of grass species and there is a 290m clear path between the transmitter and receiver. Vegetation, which included some woody species have all been cleared to reduce interference from other sources.

5.4.3 Micro-meteorological/weather station

The station measures net radiation (R_n), wind speed and direction, G, volumetric soil water content (SWC), air and soil temperature as well as relative humidity (RH). Micro-meteorological variables and instruments used are presented (Figure 5-3; Table 5-1). Two net radiometers (NRLite, Kipp and Zonen, Delft, The Netherlands) are used to measure R_n at 2 m above the canopy. The G was measured using four soil heat flux plates (HFP01, Campbell Scientific Inc., Logan, Utah, USA). The plates were placed at a depth of 80 mm below the soil surface. A system of parallel soil thermocouple probes (TCAV, Campbell Scientific Inc., Logan, Utah, USA) was installed at depths of 20 and 60 mm to measure soil temperature above the heat flux plates. A soil thermocouple probe measures temperature at four locations, or junctions, each consisting of type E thermocouple wire (chromel-constantan) that is enclosed within a stainless-steel tube (Campbell Scientific). It operates in conjunction with the soil heat flux plate to calculate the heat flux at the surface of the soil. Volumetric soil water content (CS616, Campbell Scientific Inc., Logan, Utah, USA) is measured in the upper 60 mm of soil using two sensors. The installation of heat flux plates, soil temperature thermocouples and the water content reflectometer were done following Campbell Scientific (2002). An HC2S3 temperature and RH probe (Campbell Scientific Inc., Logan, Utah, USA) was used to measure air temperature and RH. The probe is appropriate for long-term, unattended applications. Air temperature was also measured using two unshielded type-E (chromel/constantan) fine-wire thermocouples (FW05) placed at heights of 1 m and 2.7 m above the ground surface. The FW05 is a fast response Type E thermocouple with a 0.0005 in. diameter. It measures atmospheric temperature gradients or fluctuations with research-grade accuracy. Wind speed and direction were measured using an anemometer (Wind Monitor-AQ, model 05305, R.M. Young Company, Michigan, USA) locate at 2.5 m above the surface.

Table 5-1 List of instruments at the LAS Micro-Meteorological Station

Bio-meteorological variable	**Instrument**
Soil heat flux ($W.m^{-2}$)	4 x soil heat plate (HFP01) (Hukseflux Thermal Sensors, Delft, Netherlands)
Volumetric water content (%)	Water content reflectometer (CS616, Campbell Scientific Inc., Logan, Utah, USA)
Temperature and RH (%)	HC2S3 Temperature and RH Probe (Campbell Scientific Inc., Logan, Utah, USA)
Soil temperature (°C)	2 x Averaging soil thermocouples probe (TCAV, Campbell Scientific Inc., Logan, Utah, USA)
Net radiation ($W.m^{-2}$)	2 x net radiometers (NR-lite2) (Kipp and Zonen, Netherlands)
Air temperature (°C)	2 x fine wire thermocouples (FW05: 0.0005 inch /0.0127 mm, Campbell Scientific Inc., Logan, Utah, USA) at 1.0m and 2.5m above soil surface
Wind speed ($m.s^{-1}$) and direction (degrees)	Wind Monitor-AQ, model 05305, R.M. Young Company, Michigan, USA

5.4.4 Leaf porometer

A hand-held SC-1 model leaf porometer (Decagon Instruments, USA) is used to measure stomatal conductance (G_s) from the leaf of a *Cannabis sativa* plant, this measurement provides information about the difference between transpiring leaves and leaves that have closed their stomata (Meter Group, 2022). The stomata are the openings or pores found on the epidermis of leaves, stems and other plant organs, they are primarily responsible for the gaseous exchange whereby water vapour exits the plant in a process known as evapotranspiration and carbon dioxide is taken in (Esau, 1977). The CO_2 is a vital component of the process of photosynthesis which is one of the most important processes on earth (Swarthout and Hogan, 2010). This process is responsible for converting radiation or light energy into chemical energy that is utilised by plants and other organisms for survival i.e., used as fuel (Swarthout and Hogan, 2010). The stomata are therefore one of the most important organs of a plant. Stomatal conductance is defined as the rate at which CO_2 enters or H_2O exits through the stomata of the plant (Thomas et al., 2017). Gimenez et al. (2005) defines stomatal conductance as a measure of the degree of stomatal opening and measures the rate of gaseous exchange between the atmosphere and the leaf of a plant. The leaf porometer has a sensor head that is sensitive to humidity changes (Thomas et al., 2017). A leaf is clamped by the sensor head to get a reading. The leaf porometer has a sensor head that must be opened and place a leaf inside it to get a reading. This takes approximately 30 seconds when the leaf porometer is automated. The stomatal conductance is expressed in units of mmol m^{-2} s^{-1}. A random systematic sampling grid was developed on Microsoft Excel. This enables the random selection of plants ensures no repeats and removes any biases that might be introduced. Five plants are sampled every day and the data received is stored in the SC-1 leaf porometer and later captured on an excel spreadsheet, the data is also recorded on a book in case the one stored in the leaf porometer is corrupted or lost.

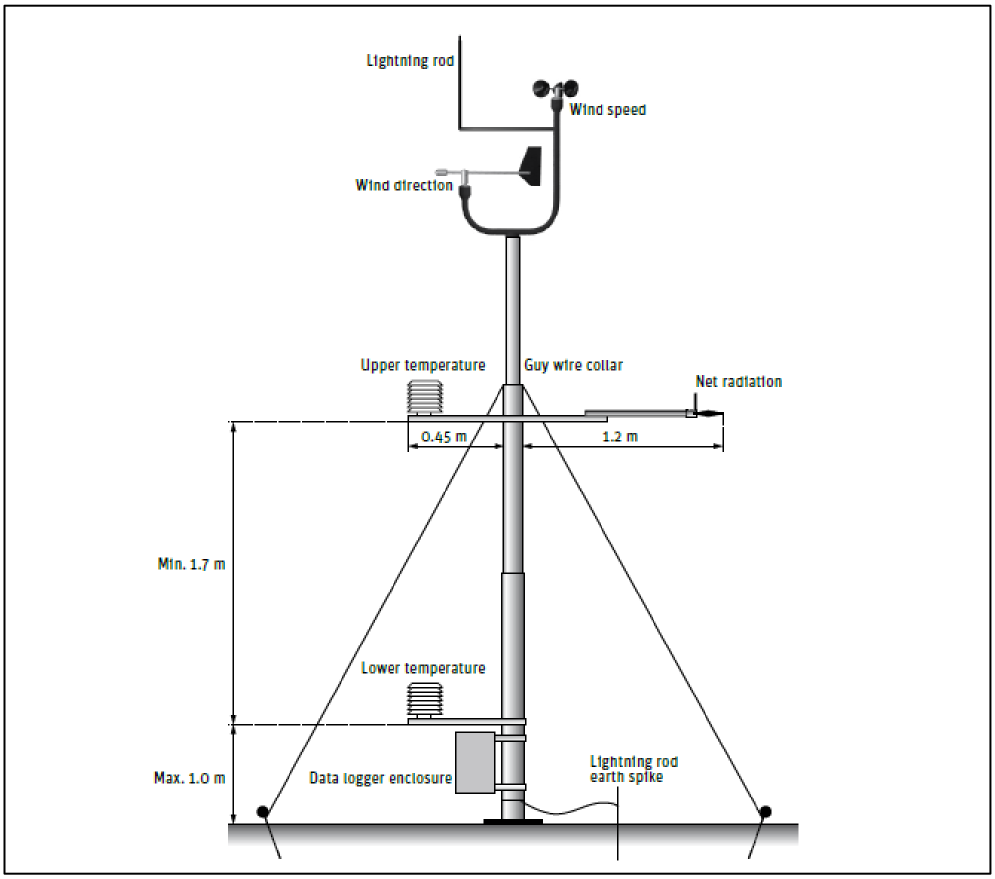

Figure 5-3 A sketch of the weather station at Firglen study site (LAS MkII, Kipp and Zonen, 2022)

5.4.5 Ceptometer

A hand-held ceptometer was used to measure the Leaf Area Index (LAI) of *C. sativa* plants in both locations, i.e., Firglen farm and Sweetwaters tunnel facility (MeterGroup, 2022). The ceptometer was also used to measure the photosynthetically active radiation (PAR).

5.5 Evapotranspiration modelling

There are numerous evapotranspiration models utilised across the globe, some are empirically based while others are physically based (Fontenot, 2004). These models have varying accuracies, some require several input parameters while others require less parameters (Fontenot, 2004). A good example of an accurate ET model that requires multiple meteorological parameters is the United Nations Food and Agriculture Organisation Penman-Monteith Model (Allen et al., 1998). Other ET models require less parameters such as the FAO 24 Radiation Method that can be utilised when there is ample sunlight i.e., radiation and air temperature and there is no wind and humidity data available and yet still yield relatively accurate results (Doorenbos and Pruitt, 1977; Allen et al., 1998). In this project the MEDRUSH model was used for modelling actual ET of the cannabis crop.

5.5.1 MEDRUSH

The version of the model used in this study was developed by Colin Osborne of the University of Sheffield, UK, and was presented at the BBSRC-funded workshop entitled "Ecophysiology Techniques Workshop" in Lisbon, Portugal from 10-15th September 2012. Stomatal conductance (g_s), a required input into the model, was measured for *C. sativa* under a range of growing conditions for both dryland and in-tunnel cultivation. The R script for the model uses the micro-meteorological data and the g_s to compute energy fluxes. The main inputs to the MEDRUSH model include: (a) physical site-specific parameters, (b) ecosystem specific parameters and (c) meteorological data. The meteorological data used by MEDRUSH include 20 min minimum and maximum temperature, relative humidity, soil temperature, wind speed and solar radiation. All data were obtained from the weather station at the site.

The performance of the MEDRUSH model against the ET measured by the LAS was evaluated using several performance metrics including mean absolute error (MAE), root mean square error (RMSE), RMSE-observations standard deviation ratio (RSR) and percent of bias (PBIAS). These metrics aid in knowing how accurate the model is at estimating or predicting the observed data, in our case evapotranspiration from the LAS.

5.6 Results

The data represents the baseline data before the *Cannabis sativa* was planted and after it was planted. It also represents the local grass found in the region which is *Eragrostis plana*. This enabled the researchers to know the prevailing conditions of the study i.e., the evapotranspiration coming from the local vegetation before the planting of *C. sativa* and after. The data was obtained from the Firglen study site using the LAS and the weather station.

5.6.1 Description of the LAS at Firglen

The effective height of the LAS at Firglen was 1.83 m. The location of the path length (beam) and the underlying surface topography at the two study sites are presented (Figure 5-4) below. The distance between the transmitter and the receiver was 354 m, the elevation at the transmitter was 569 m while the elevation at the receiver was 582 m.

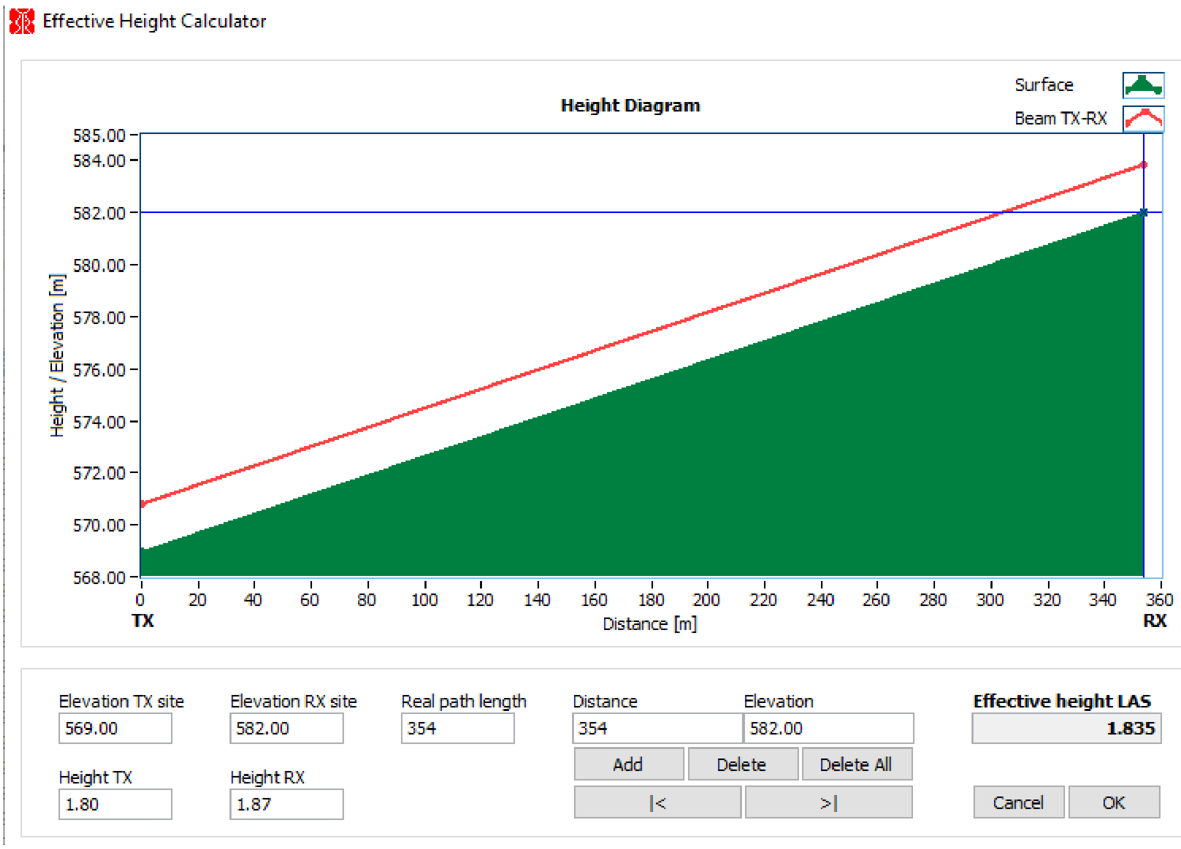

Figure 5-4 Path length beam and underlying surface topography between the LAS transmitter (TX) and receiver (RX) at Firglen

5.6.2 Meteorological attributes of Firglen study site

The meteorological station attached to the LAS measured wind speed, air temperature, relative humidity, net radiation, air pressure, wind direction and soil temperature. All these parameters are plotted below. Table 5-2 also illustrates the summary of the weather conditions during the study period at Firglen.

The thermocouple that was situated at a lower position on the mast exhibited a higher temperature (mean± standard deviation: 16.63 ± 6.27°C) when compared to the upper thermocouple (mean± standard deviation: 15.86± 5.40°C). The Air Temperature exhibited the highest temperature (mean± standard deviation: 18.30± 6.12°C) when compared to upper and lower temperatures as illustrated in Table 5-2 below.

Table 5-2 Summary of meteorological conditions during the study

Descriptive statistics		Mean	Standard deviation	Max	Min
Thermocouple (upper)(˚C)	**T**	15.86	5.40	38.86	0.77

Thermocouple T (lower) (˚C)	16.63	6.27	44.60	-0.05
Air T (˚C)	18.30	6.12	44.60	2.21
Relative humidity (%)	73.43	20.85	109.80	7.81
Atmospheric pressure (kPa)	96.23	10.60	100.30	NA
Wind speed (m sec^{-1})	2.025	1.94	14.39	0.00
Soil temperature (˚C)	16.85	5.55	40.72	6.17
Soil moisture (%)	22.45	6.21	25.97	17.83
Heat flux (Watts m^{-2})	0.70	31.90	143.30	-64.38

Air temperature was measured over a period of 12 months beginning in October 2021 to October 2022 (Figure 5-5). The highest temperatures were recorded in the month of January 2022, the highest recorded temperature was 38,86˚C and the lowest temperature recorded was in August 2022, it was 0.77˚C. The temperature over the 12 months period is illustrated in the graph below. The highest temperatures were measured between the months of January and March (mean± standard deviation: 23.77 ± 3.05) while the lowest average temperatures were measured in between the months of April and August 2022.

Windspeed was also recorded over 12 months from 2021 to 2022 (Figure 5-6). The highest windspeed was measured between the months of November and December 2021, the highest windspeed measured was 14.39 m sec^{-1} in November 2021 and the average windspeed was (mean± standard deviation: 2.03 ± 1.94 m sec^{-1}).

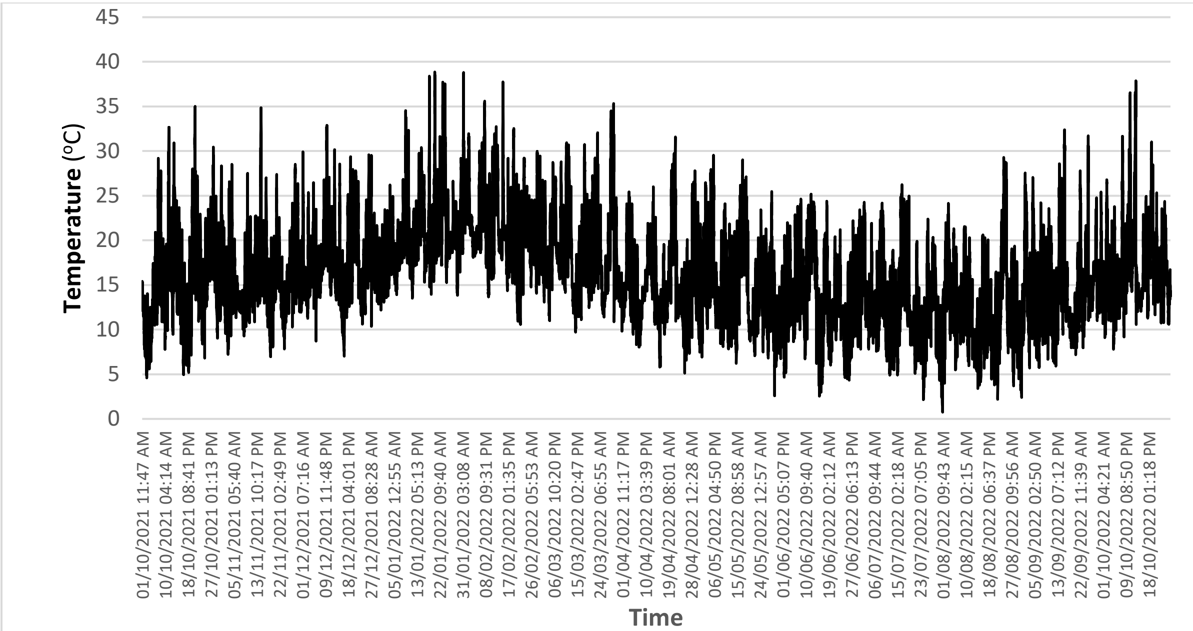

Figure 5-5 Air temperature (T_{air}) on Firglen during the first 12 months of the study

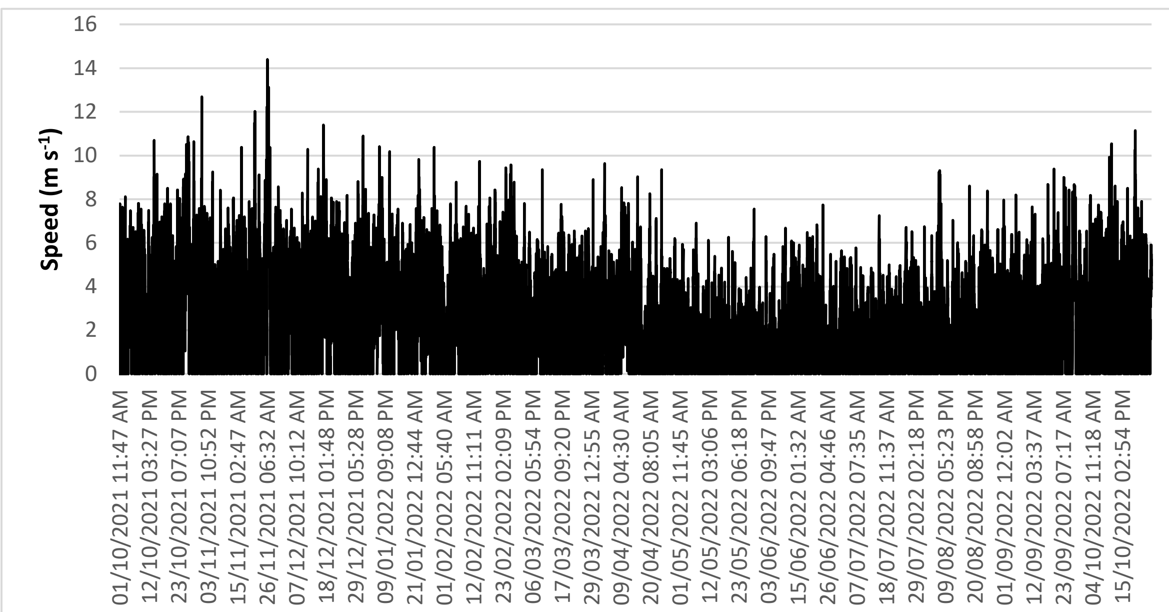

Figure 5-6 Maximum windspeed (m sec^{-1}) on Firglen during 18 months of the study. On many days during the growing season, the wind speed exceeds 8 m sec^{-1} which is extreme for Cannabis under dryland conditions.

Soil moisture is one of the parameters that were measured during the same period of time as the other parameters such as windspeed or temperature. Figure 5-7 shows that the highest soil moisture was recorded between November and December 2021 and again between April and May 2022, while the lowest soil moisture was measured in the months of January and February 2022. The clear wet and dry season pattern indicates how important it is to be able to apply irrigation to maintain soil moisture throughout the growing season. Rapid fluctuations in soil moisture during the wet season, linked to high evaporative demand, further support the need to be able to provide emergency irrigation under dryland conditions. The average windspeed throughout the period was (mean± standard deviation: 16.85 ± 5.55) which is below the optimum soil moisture needed by cannabis which is 23%.

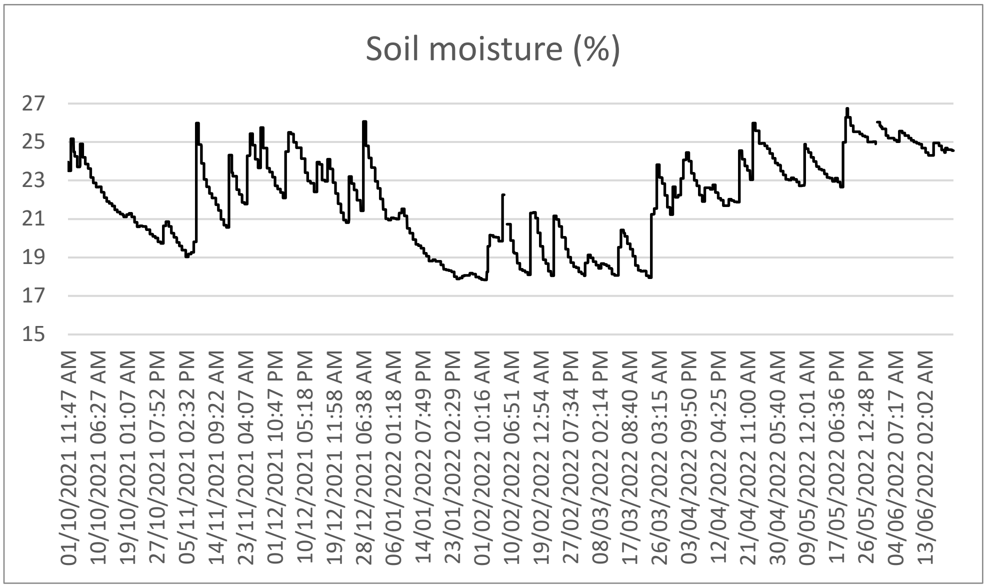

Figure 5-7 Soil moisture recorded throughout the study period

The Firglen study site is situated in a valley and is therefore prone to katabatic winds also known as bergwinds in summer. This phenomenon has resulted in less-than-ideal conditions for the plants. It can be observed in Figure 5-8 that the occurrence of bergwinds which are associated with increased temperatures leads to lower soil moisture. The months of January and February exhibited the highest air temperatures and the bergwinds were strongest during that period. It can be observed that the soil moisture decreases with increased occurrence of bergwinds.

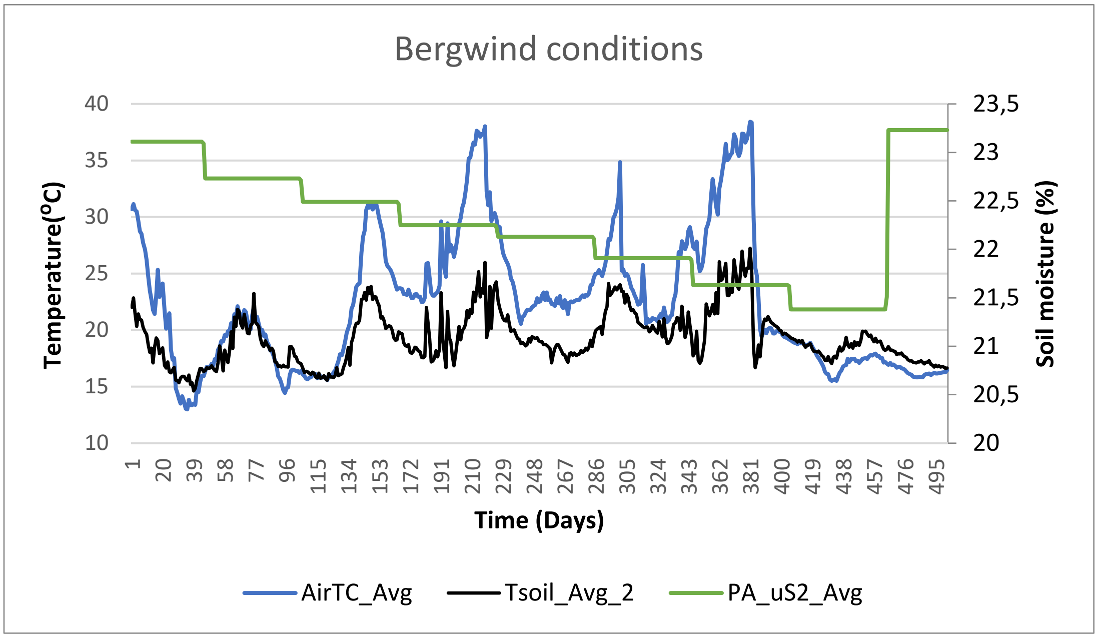

Figure 5-8 Bergwind conditions experienced at Firglen Study site over a period of 8 days. Periods of high air T (AirTC_Avg), high soil T (Tsoil_Avg_2) are accompanied by a decline in soil moisture (PA_uS2_Avg).

5.7 Results: Stomatal conductance and other measured parameters

5.7.1 Stomatal conductance first trial early to mid-2022

The stomatal conductance of the two species viz *C. sativa* and *E. plana* were measured at Firglen study site from March to May 2022. *Cannabis sativa* exhibited higher stomatal conductance (g_s) (mean± standard deviation: 276.31±153.36) when compared to the grass (mean± standard deviation: 67.45±37.68). The month of March exhibited the highest stomatal conductance in *C. sativa* while the highest gs in grass was observed during the month of May 2022 (Figure 5-9 and Figure 5-10). The month of April had the lowest g_s in both *C. sativa* and grass. The trend exhibited by the graph is that with the change of seasons from summer warmer months to winter cooler months the stomatal conductance gradually decreases as shown (Figure 5-9). The month of March exhibited the highest stomatal conductance. The data is not normally distributed so a Wilcox test was performed and $p<0.01$ which shows that there is a significant difference between the g_s of *Cannabis sativa* and that of *Eragrostis plana.*

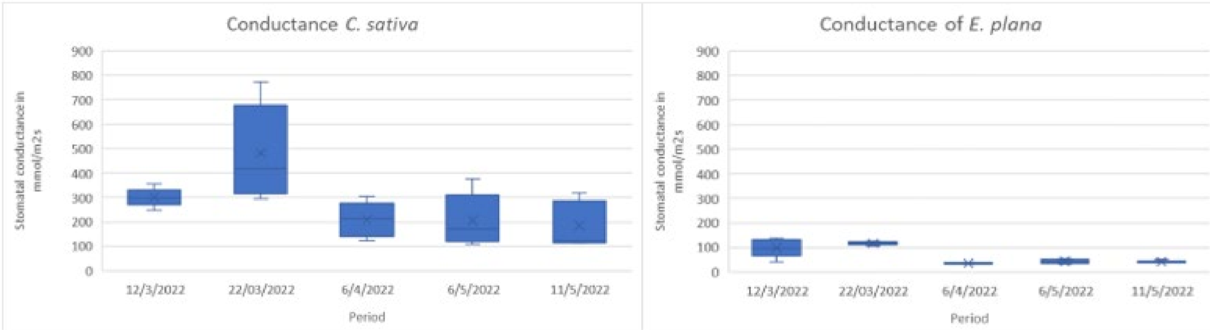

Figure 5-9 Stomatal conductance between the dominant local grass (E. plana) and Cannabis sativa at Firglen in 2022

5.7.2 Stomatal conductance late 2022 to 2023

Stomatal conductance (gs) of actively growing healthy *C. sativa* was measured from December 2022 to January 2023. The 9th of December exhibited higher gs when compared to the 3rd of January 2023 (mean±standard deviation 847.31±142.5 mmol m^{-2} s^{-1}) (mean±standard deviation 623.16±160.59 mmol m^{-2} s^{-1}) respectively. A t-Test on stomatal conductance was performed for both days and the p-value= 0.000542 showing that there was a significant difference between the two days (Figure 5-10).

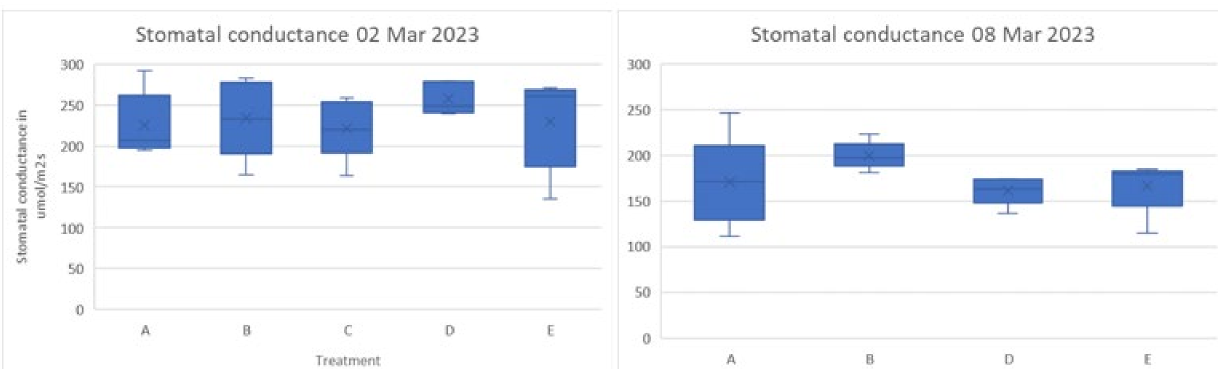

Figure 5-10 Stomatal conductance on two days towards the end of the crop cycle (2 and 8 March 2023)

The 2 March exhibited higher g_s (mean± standard deviation 724.85±111.98 mmol m^{-2} s^{-1}) when compared to the 8 March (mean± standard deviation 551.34±118.52 mmol m^{-2} s^{-1}) (Figure 5-10).

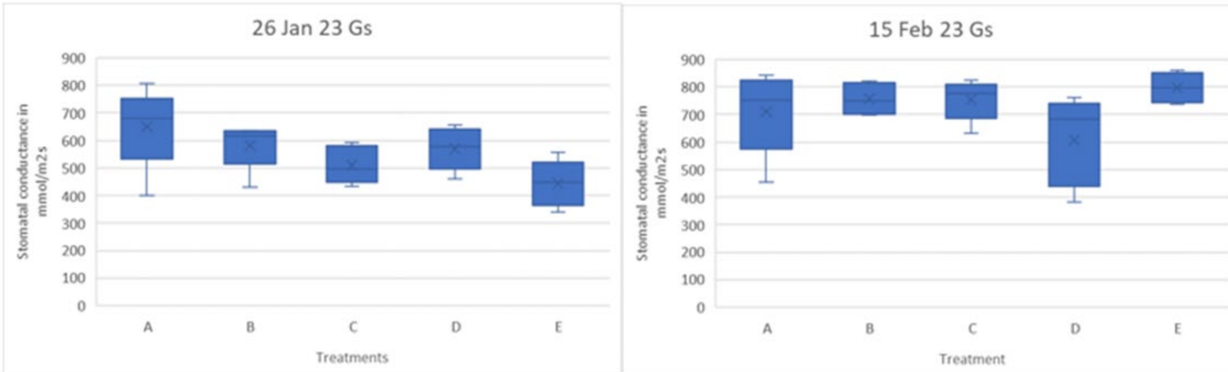

Figure 5-11 Stomatal conductance on 26 Jan and 15 Feb 2023 during the height of the crop cycle

There is a significant difference between the two days ($p<0.01$). The two days in March exhibited the lowest eg$_s$ when compared to all the other previous days. The 2nd of March showed a higher gs (mean± standard deviation 173.85±32.83 mmol m^{-2} s^{-1}) when compared to the 8th March (mean± standard deviation 233.59±39.72 mmol m^{-2} s^{-1}). There is a significant difference between the two days of March ($p<0.01$).

5.7.3 Other measured parameters: Different treatments

In January, fertilizer was applied to certain sections of the cropping area, below is the summary of the data obtained from these different sections.

The data was collected from five different sections of the cropping area at Firglen. The first three sections namely A, B and C received fertilizer (organic NPK) while D and E did not receive any fertilizer. Section B and Section D grow on mounds or contours while the other three grow on a flat surface traditionally used for cropping. An analysis of variance (ANOVA) was performed on stomatal conductance data on the 3rd of January, it showed no significant difference between sections or treatments (Table 5-3). While the data collected on the 26th showed a significant difference between E-A (p-value = 0.02), there was no significant difference among the other treatments (Table 5-4).

Leaf area index (LAI)

Leaf area index was measured on different days starting in December 2022 to March 2023. The 9th of December has an overall higher LAI (mean± standard deviation 2.55±0.66) when compared to the 3rd of January (mean± standard deviation 2.25±1.2). However, some treatments on the 3rd have higher LAI than the 9th for example treatment C on the 9th has higher LAI when compared to the 3rd (Figure 5-12). There is no significant difference between the two treatments ($p=0.32$).

The two days of January 26 and February 15 do not follow a similar trend in LAI (Figure 5-13). On 26 January, the LAI is relatively uniform while on the 15th the LAI increases from treatment A to E, with E having the highest LAI. The 26th had the higher LAI (mean± standard deviation 0.90±0.35) when compared to the 15th (mean± standard deviation 0.72±0.13). There is a significant difference between the two days (p=0.003).

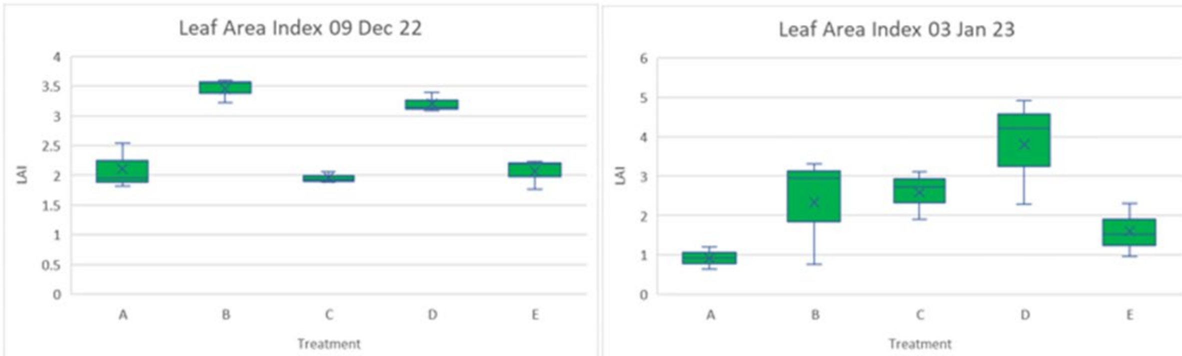

Figure 5-12 Leaf area index at Firglen for 9 Dec 2022 and 03 Jan 2023

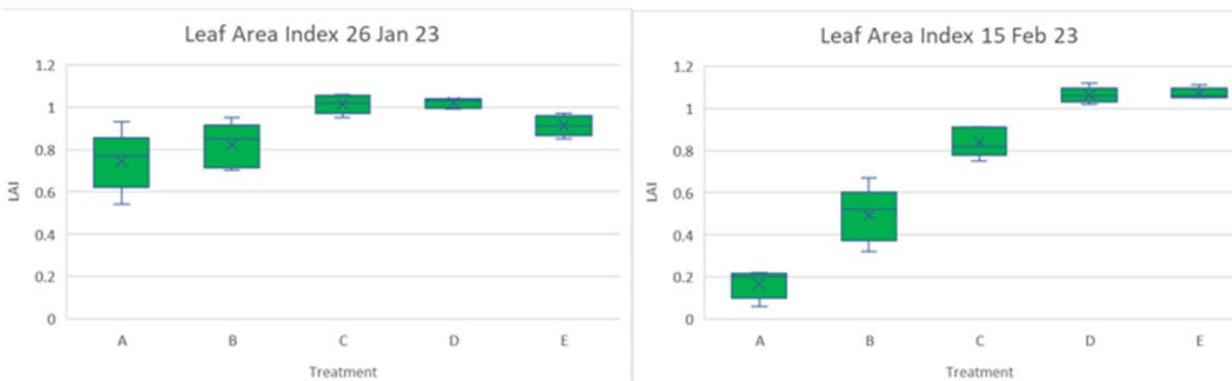

Figure 5-13 Leaf area index at Firglen for 26 Jan 2023 and 15 Feb 2023

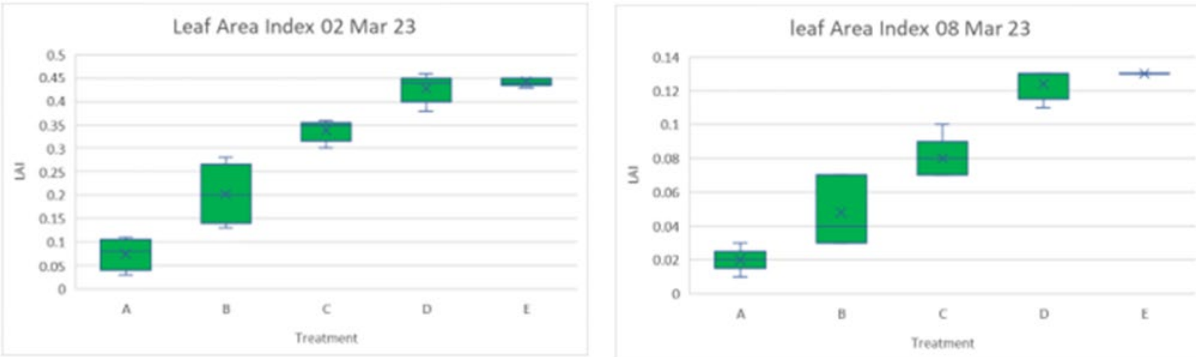

Figure 5-14 Leaf area index at Firglen for 02 Mar 2023 and 08 Mar 2023

The two days follow a similar trend to the one observed on the 15 of February whereby the LAI gradually increases from treatment A up to E. the 2nd of March had a higher average LAI (mean± standard deviation 0.29±0.14) than 8th of March (mean± standard deviation 0.08±0.04). The 8th of March had the lowest LAI off the measured days (Figure 5-14).

Among the different treatments on 3rd January 2023 there was significant difference between treatments B-A, D-A and E-D but not significant difference between C-A, E-A, C-B, D-B, E-B, E-C and E-D sections (Table 5-3).

On the 26th there was a significant difference between C-A, D-A, E-A, C-B, D-B, E-B and no significant difference was found between B-A, D-C, E-C and E-D treatments (Table 5-4).

Table 5-3 TukeyHSD showing p-value between the different treatments on the 3rd of January 2023

	TukeyHSD p-value			
Treatments	**Conductance**	**Leaf Area Index**	**Height**	**Width**
B-A	0.9935767	0.0188413	0.0004459	0.0776289
C-A	0.7651426	0.0974905	0.0422139	0.5657722
D-A	0.9995573	0.0003824	0.0001069	0.0095785
E-A	0.4738634	0.9158491	0.3821808	0.7682331
C-B	0.9377559	0.9278829	0.2796346	0.7179750
D-B	0.9707148	0.4344160	0.9658829	0.8570064
E-B	0.7180874	0.1048003	0.0268822	0.0064142
D-C	0.6458528	0.1217013	0.0906608	0.2029632
E-C	0.9870092	0.3910033	0.7292588	0.0924483
E-D	0.3614165	0.0025265	0.0065534	0.0006879

Table 5-4 TukeyHSD showing p-value of the different treatments on the 26 of January 2023

Treatments	**Conductance**	**Leaf Area Index**	**Height**	**Width**
B-A	0.8050125	0.6023494	0.1100729	0.2635802
C-A	0.1999187	0.0005496	0.0561451	0.5415434
D-A	0.6913165	0.0004276	0.0136018	0.0603569
E-A	0.0243996	0.0375753	0.2175975	0.1870542
C-B	0.7740365	0.0143939	0.9967264	0.9827276
D-B	0.9995619	0.0112540	0.8467537	0.9238931
E-B	0.2074299	0.4692347	0.0009297	0.0023696
D-C	0.8727644	0.9999613	0.9610379	0.6673766
E-C	0.8159914	0.3488177	0.0004285	0.0078689
E-D	0.2884668	0.2960025	0.0000974	0.0003796

Height

The 3rd of January had taller plants (mean± standard deviation 0.97±0.15) when compared to the 9th of December (mean± standard deviation 0.79±0.20). On 3rd January 2022, the A section had the shortest plants while section D had the tallest plants (Figure 5-15; Figure 5-16). There is a significant difference between the two measured days ($p=0.005$).

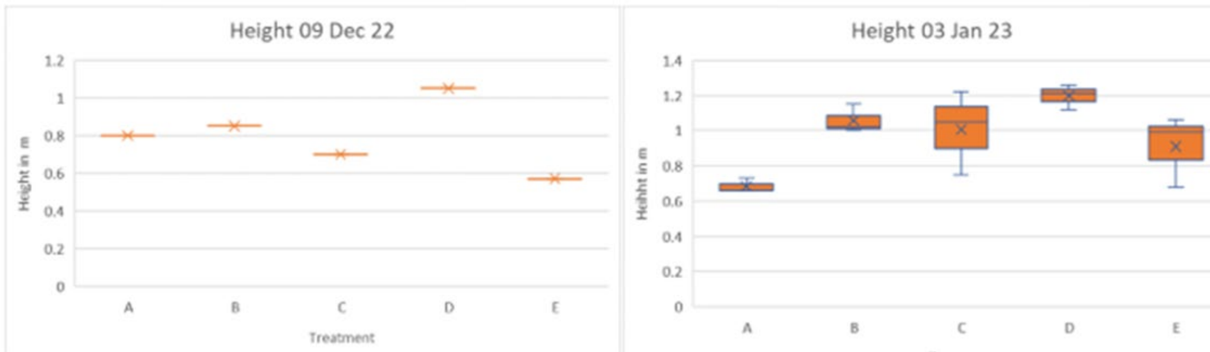

Figure 5-15 Height of C. sativa on 9 Dec 22 and 03 Jan 23

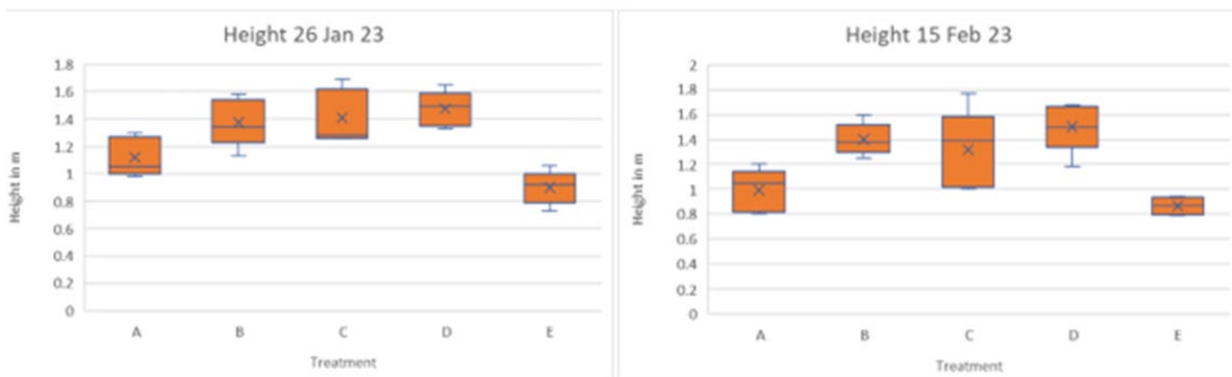

Figure 5-16 Height of C. sativa on 26 Jan 23 and 15 Feb 23

The height of the plants on the 26th of January were slightly taller (mean± standard deviation 1.25±0.25 m) than those from the 15th of February (mean± standard deviation 1.21±0.29 m). On the 26th of January 2023, section E had the shortest plants while section C had the tallest plants (6). On both days, section A and E had shortest plants when compared to the other three treatments. The plants growing on mounds (section B and D) had the tallest plants, C also had tall plants on the 26th despite not growing on the mound. There was no significant difference ($p=0.48$) in the height of the plants during these two days. The plants that were measured on the 2nd of March were on average taller (mean± standard deviation 1.22±0.22 m) than those of the 8th (mean± standard deviation 1.15±0.41 m). Despite this some plants on the 8th were taller than plants on the 3rd, this can be observed in treatment C on the 8th, plants in treatment C were the tallest on both days (Figure 5-17). This indicates that there is no significant difference ($p=0.37$) in plant height between the two days.

It can be clearly observed from the data that the plants have been growing taller starting from December 2022 to March 2023 with the most change occurring between December and January.

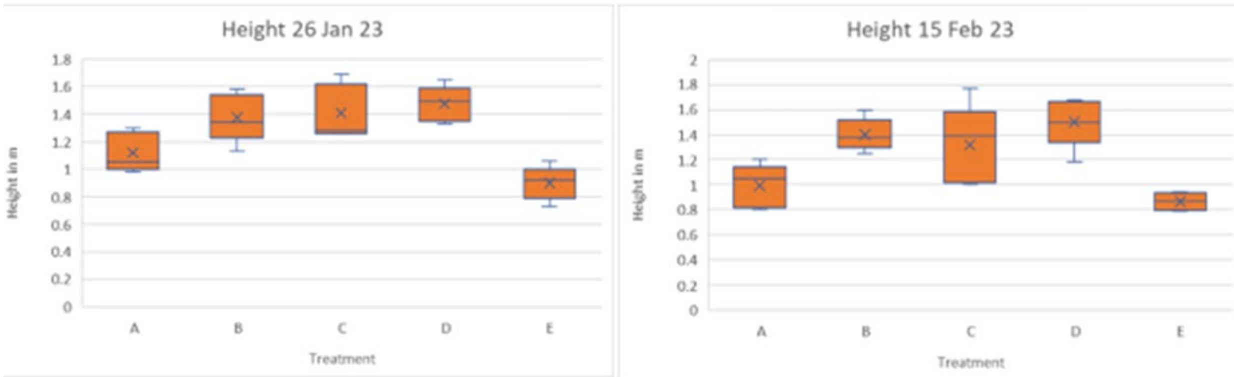

Figure 5-17 Height of C. sativa on 26 Jan 23 and 15 Feb 23

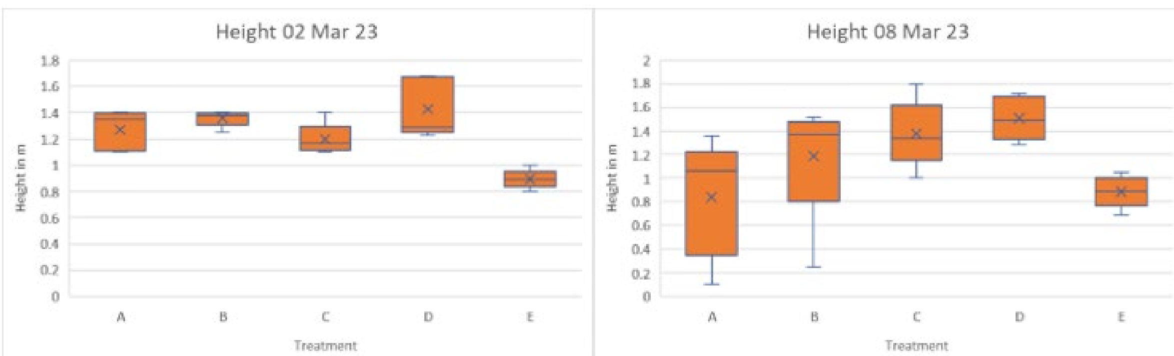

Figure 5-18 Height of C. sativa on 02 Mar 23 and 08 Mar 23

Width

The plants on the 3rd of January were wider (mean± standard deviation 0.58±0.30 m) than those of the 9th (mean± standard deviation 0.58±0.19 m). Despite this, there was no significant difference in the width of the plants (p=0.66). The widest plants were found in treatment D on the 3rd of January and the least wide were in treatment C on the 9th of December (Figure 5-19).

The 26th had wider plants (mean± standard deviation 0.62±0.19) than the 15th (mean± standard deviation 0.57±0.24) with treatment B on the 26 having the widest while treatment E on the 15 had the least wide plant (19). There is no significant differece (p=0.12) between the plants.

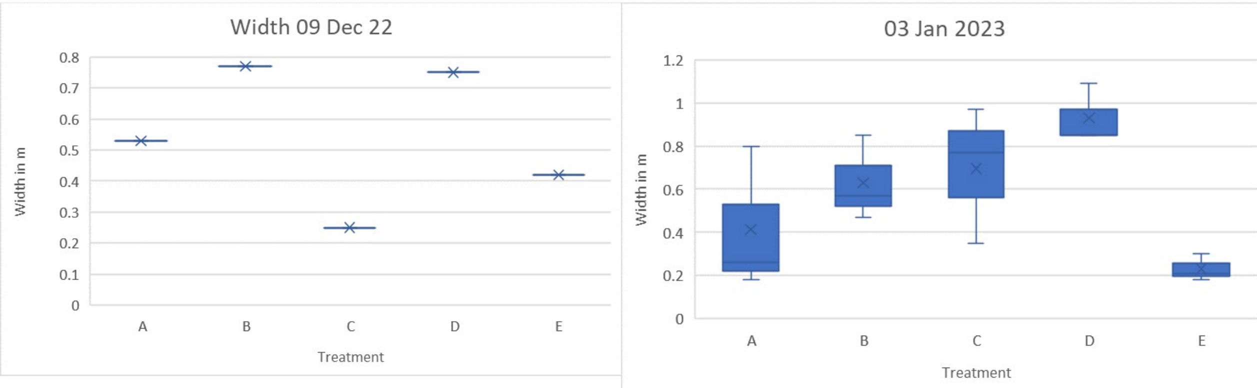

Figure 5-19 Width of C. sativa *on 09 Dec and 03 Jan*

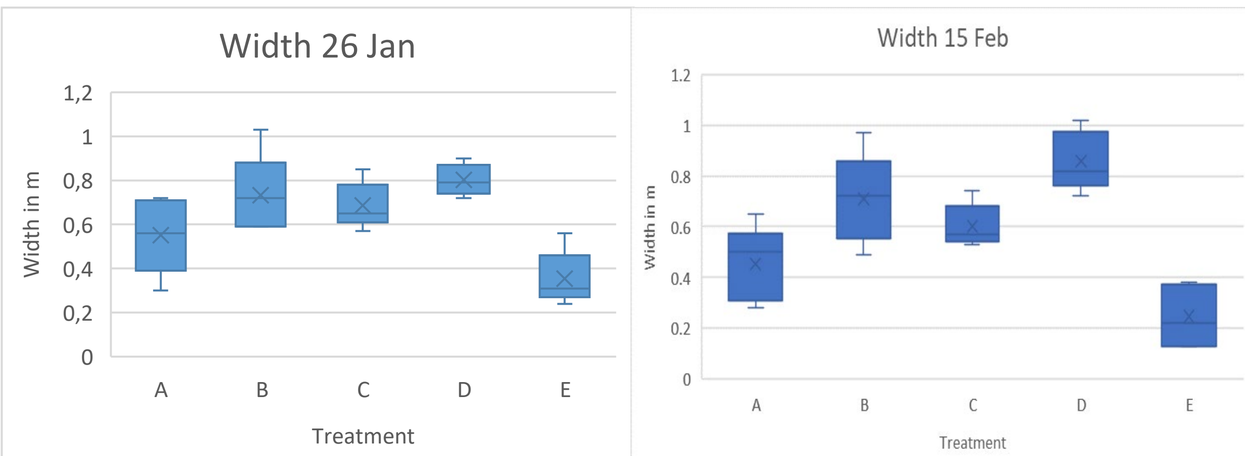

Figure 5-20 Width of C. sativa *on 26 Jan and 15 Feb 2023*

The plants measured on the 8th (mean± standard deviation 0.62±0.31) were wider than those measured on the 3rd (mean± standard deviation 0.57±0.23 m) with treatment D on both days showing the highest values for width (Figure 5-20). There was no significant difference (p=0.20) between the width of these plants in the two days of measurement.

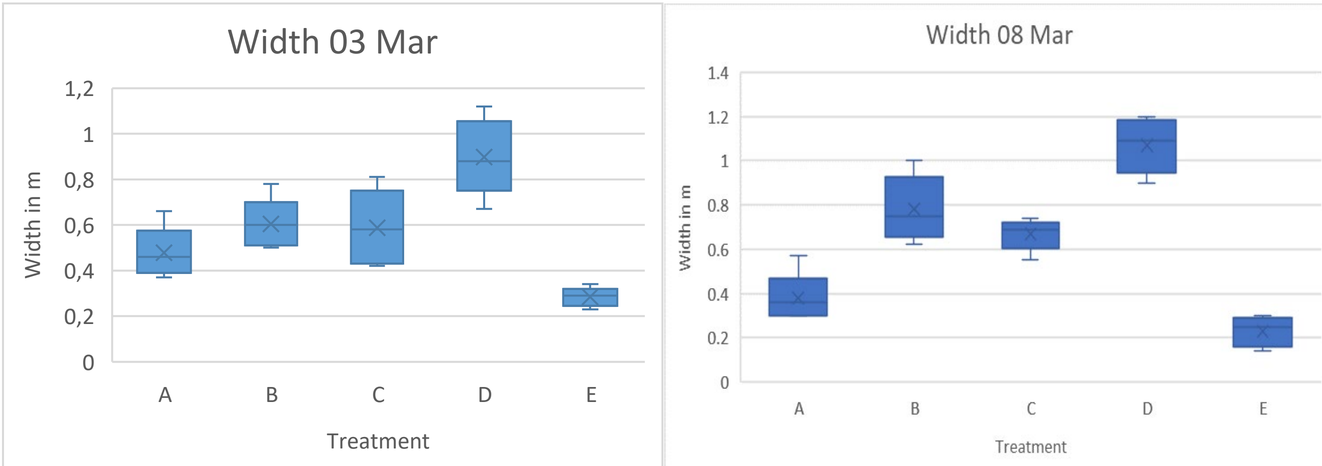

Figure 5-21 Width of C. sativa *on 03 Mar and 08 Mar 2023*

The width of these plants follows a similar trend to that of height, as the time progresses so does the width indicating growth over the growing cycle.

5.8 Results: Experiments at Sweetwaters

Data collection at Sweetwaters Cannabis Facility commenced in June 2022 and ended in August 2022. The data was collected using a hand-held leaf porometer for measuring stomatal conductance, a ceptometer to measure leaf area index and photosynthetically active radiation and a tape measure to measure the height and width of the plants. The data was measured on three separate occasions. The data was collected from three different treatments. The treatments differ according to the amount of water they receive and the growing medium. Some are grown in aquaponics, others in soil, and others in bags.

The stomatal conductance from three different treatments varied. The aquaponics treatment exhibited the highest stomatal conductance values while the plants grown in bags exhibited the lowest values (Figure 5-21).

The leaf area index (LAI) also varied among the different treatments the plants were growing under. The plants grown in bags exhibited the highest LAI while the plants grown directly in the soil exhibited the lowest LAI.

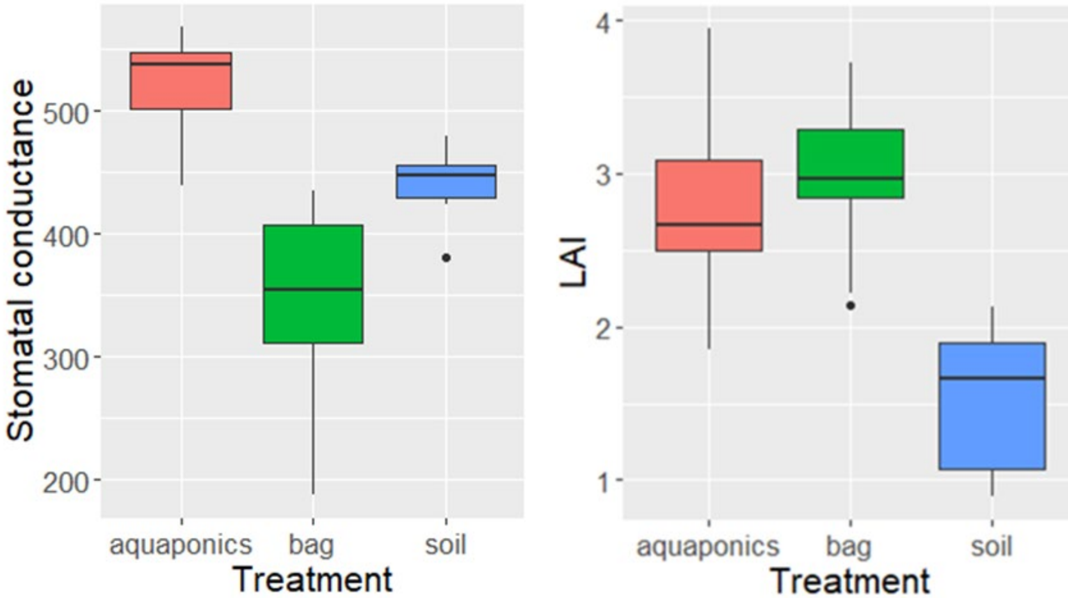

Figure 5-22 Stomatal conductance and leaf area index of each treatment at Sweetwaters

5.9 Parameter estimation and validation at Firglen farm

Table 5-5 below shows the difference between MEDRUSH (g=10) and MEDRUSH (g=5). MEDRUSH (g=10) and MEDRUSH (g=5) represent *Cannabis sativa* planted in early February 2022 at Firglen and the local grass at Firglen *Eragrostis plana,* respectively. It shows that the daily modelled mean evapotranspiration is higher in MEDRUSH(g=10) which is *Cannabis sativa* (3.7 mm) when compared to MEDRUSH(g=5) which has a mean ET of 1.88 mm.

MEDRUSH is the model which is used to predict daily ET and it is compared to the actual ET which is obtained by using the LAS in at Firglen study site. In the table the values of the MAE, RMSE and RSR for *C. sativa* are larger than those of *E. plana* as observed in Table 5-5. The percent of bias (PBIAS) for *C. sativa* is negative while that of *E. plana* is positive. The daily ET of *C. sativa* is also higher when compared to the daily ET of *E. plana.*

Table 5-5 Model performance at Firglen illustrating the difference between C. sativa (MEDRUSH 10) and E. plana (MEDRUSH 5)

Statistics	**MEDRUSH (g=10)**	**MEDRUSH (g=5)**
MAE (mm)	0.11	0.077
RMSE (mm)	0.172	0.104
RSR	1.6	0.977
PBIAS (%)	-55.1	22.4
Daily modelled mean ET (mm)	3.7	1.88

The performance metrics data or error metrics from various days from October 2022 before the planting of *C. sativa* to November when plants were first planted to December and January when plants were fully grown is illustrated in Table 5-6. The error metric for this model have relatively low values and a negative PBIAS (Table 5-6).

Table 5-6 Model performance at Firglen

Statistics	**MEDRUSH**
MAE (mm)	0.113
RMSE (mm)	0.163
RSR	0.082
PBIAS (%)	-16.18
Daily modelled mean ET (mm)	1.82
Observed ET mm (LAS)	1.82

There is a correlation between the MEDRUSH model and the observed LAS ET (Figure 5-23). There is some underestimation done by the model but overall, the model follows the trend of the ET measured by the LAS. This is further illustrated by the small difference between the observed daily ET which is 1.824 mm and the predicted ET which is 1.815 mm.

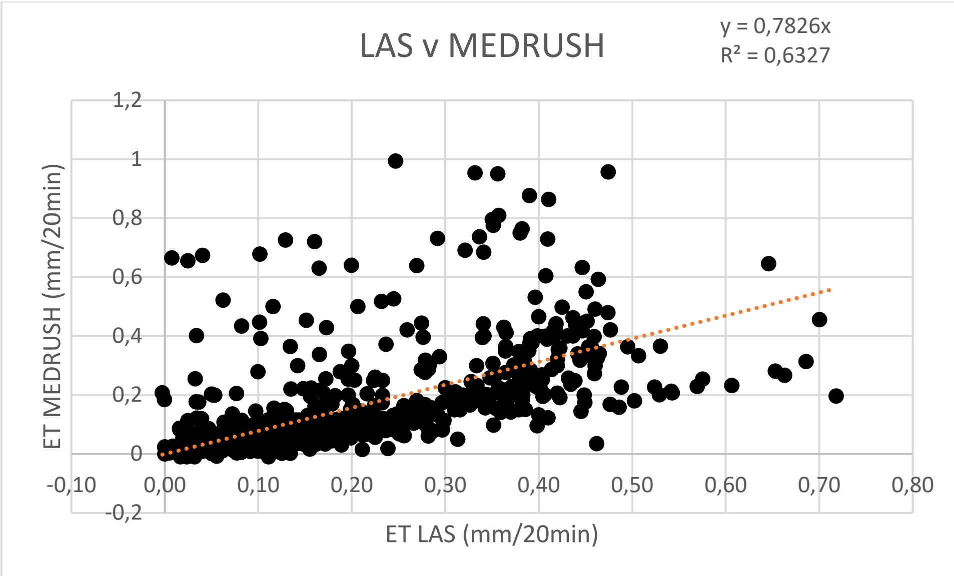

Figure 5-23 The correlation between LAS and MEDRUSH for the entire duration of the crop cycle

The MEDRUSH model and LAS follow a similar trend on the 23rd of December. On this day, the MEDRUSH model had the best estimation of LAS ET (Figure 5-24). Although MEDRUSH underestimates the daily ET, for example the highest LAS ET was 0.5 while the Highest MEDRUSH was 0.38. This trend of underestimation has been observed on other days as well. Despite this underestimation the model closely follows the trend of the LAS and the magnitude of difference in the daily ET between LAS and MEDRUSH is small.

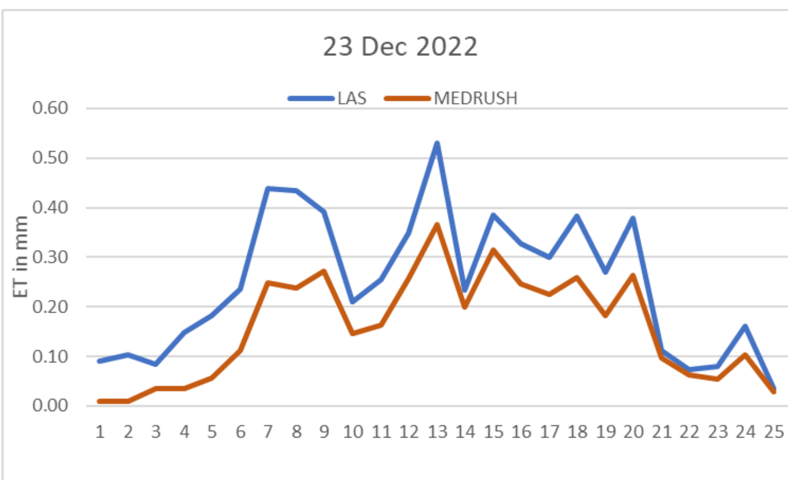

Figure 5-24 Actual ET between MEDRUSH and LAS for the 23 December 2022

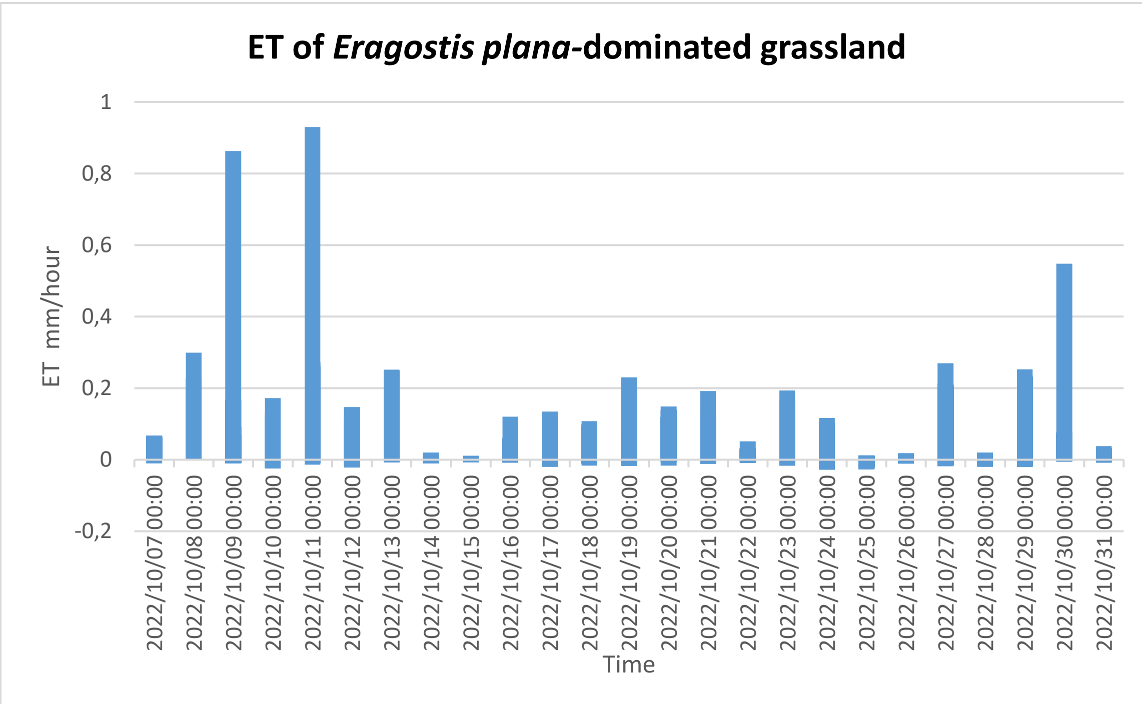

Figure 5-25 The background ET (mean hourly rate) of E. plana-dominated grassland over a time period of 30 days in the 2021-22 growing season

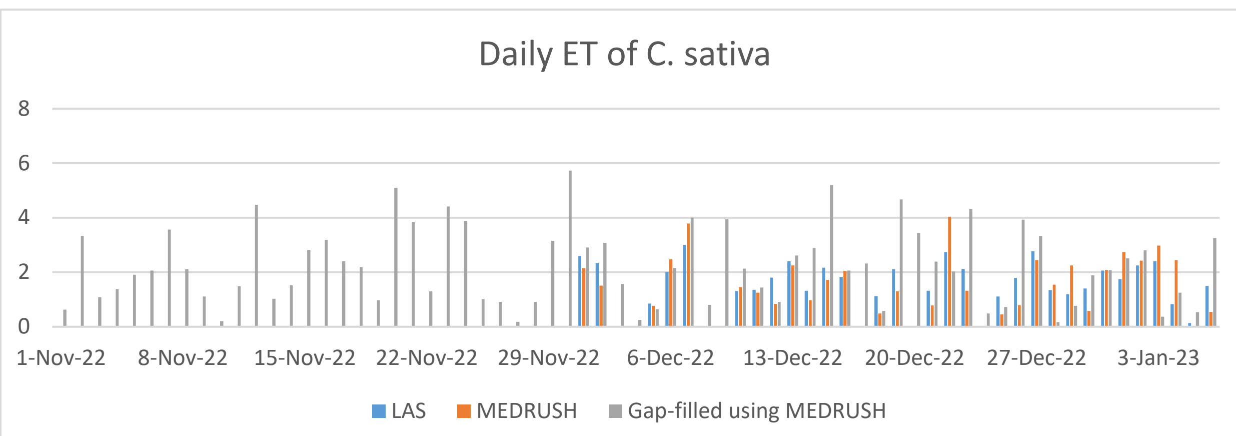

Figure 5-26 Evapotranspiration of Cannabis sativa over a period of 71 days during the peak growing period from November 2022 to January 2023 showing the valid LAS data, and the modelled MEDRUSH output for both validation and gap-filling.

Figure 5-25 illustrates the evapotranspiration of a grassland dominated by *Eragrostis plana.* The highest ET occurred on the 22nd of December 2021 with a value of 3.62 mm day^{-1}. The figure indicates that the mean daily rate of ET for *E. plana* is lower than that of *C. sativa* during the latter growing period. During the *C. sativa* trial reported here, all *E. plana* and other grasses had been treated with glyphosate and did not contribute to the ET from *C. sativa* during the trial reported here.The month of December exhibited the highest ET values. The mean ET (mm hour^{-1}) of *E. plana* during this period is 0.04 ± 0.1.

Figure 5-26 illustrates the rate of evapotranspiration of *C. sativa* from 1 November 2022 to the beginning of January 2023. The average ET over this period was 2.17±1.35 mm day^{-1} whilst the highest modelled daily ET 5.73 mm day^{-1}on the 30 November 2022.

The mean daily ET rate of all the valid readings from the LAS was 1.82± 0.64 mm day^{-1}. When MEDRUSH5 was used to model daily ET for the exact same valid periods of the LAS, the mean daily rate for the same period was 1.82 ± 1.04 mm day^{-1} (Figure 5-27). There was no significant difference between these two values.

The highest daily ET rate measured by the LAS was 3.01 mm/day on the 7th of December 2022.

When MEDRUSH5 was used to gap-fill all the days from the beginning of the growing season and to gap-fill all the missing hours in the valid LAS data, the mean daily ET was 2.17± 1.35 mm day^{-1}. This should be considered the final daily use figure for *C. sativa* under dryland production.

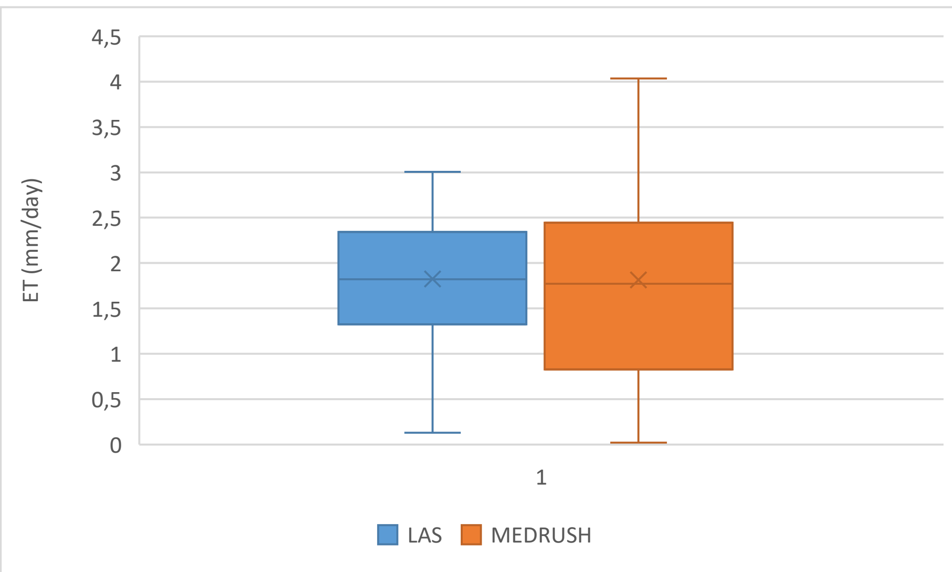

Figure 5-27 Boxplot of the daily ET measured by the LAS and that modelled by MEDRUSH for the valid LAS readings between 1 December 2022 and 7th of January 2023.

5.9.1 Variation in ET

The MEDRUSH (g=5) was able to follow the dynamics of ET measured by the Large Aperture Scintillometer (LAS) at Firglen although its correlation is slightly less than the *C. sativa* one (Figure 5-28).

Figure 5-28 further illustrates the relationship between the two methods using a line graph. The two methods follow a similar trend especially in the beginning and towards the middle. Despite the similar trend, there are also other differences between MEDRUSH (g=5) and LAS these differences are more pronounced between the months of February and the end of March.

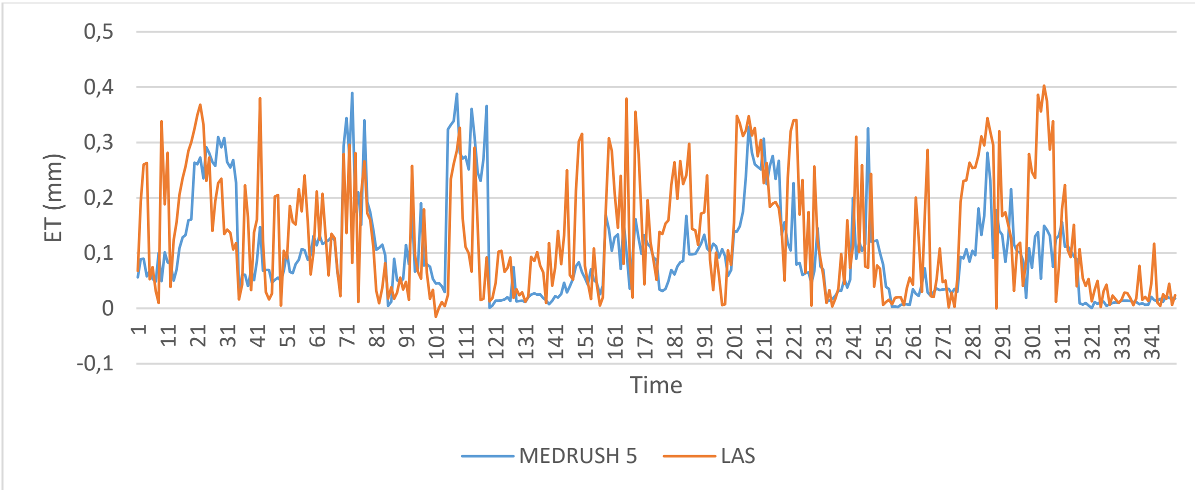

Figure 5-28 Twenty min ET for LAS and MEDRUSH at gs=5

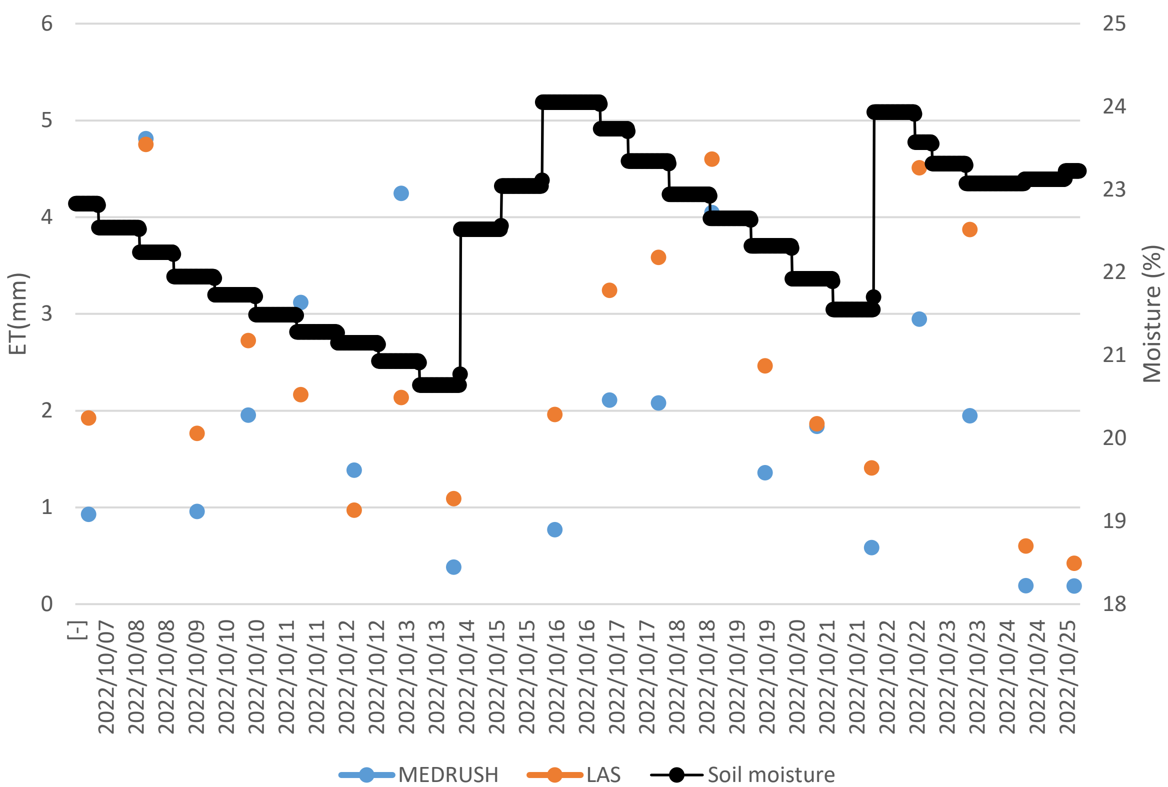

Figure 5-29 Daily total ET for the MEDRUSH model and LAS plotted with soil moisture.

Soil moisture has been plotted with MEDRUSH(g=5) and LAS output (Figure 5-29) below for the month of October 2022. There is a trend in which a decrease in soil moisture also results in a decrease in daily total ET. This trend can be clearly observed from the 17th to the 22nd of October 2022. There is also a trend whereby an increase in soil moisture leads to an increase in daily ET especially between the 13th and 16th of October. Therefore, there is a positive correlation between soil moisture and total ET.

Daily variation in measured evapotranspiration (LAS ET) during the pre-planting period when only grass (*Eragrostis plana*) was growing in the fetch (Figure 5-30). This provides the background values for ET without *Cannabis sativa* crop. As the crop was planted under no-till conditions (which is standard procedure for legacy farmers), this represents the actual background ET that exist before a crop is planted. In the figure below it can be observed that an increase in radiation results in an increase in evapotranspiration, which signifies a positive correlation between radiation and ET. The Highest latent heat of Evaporation (LvE) coming from the grass was measured at approximately 550 W/m^2 (Watts/meter squared) with radiation (Rn) of about 660 W/m^2. A trend can be observed in Figure 5-30, whereby the radiation and evapotranspiration increase exponentially during the morning and peak during midday and then decrease rapidly in the evening. All the other measured parameters follow a similar trend.

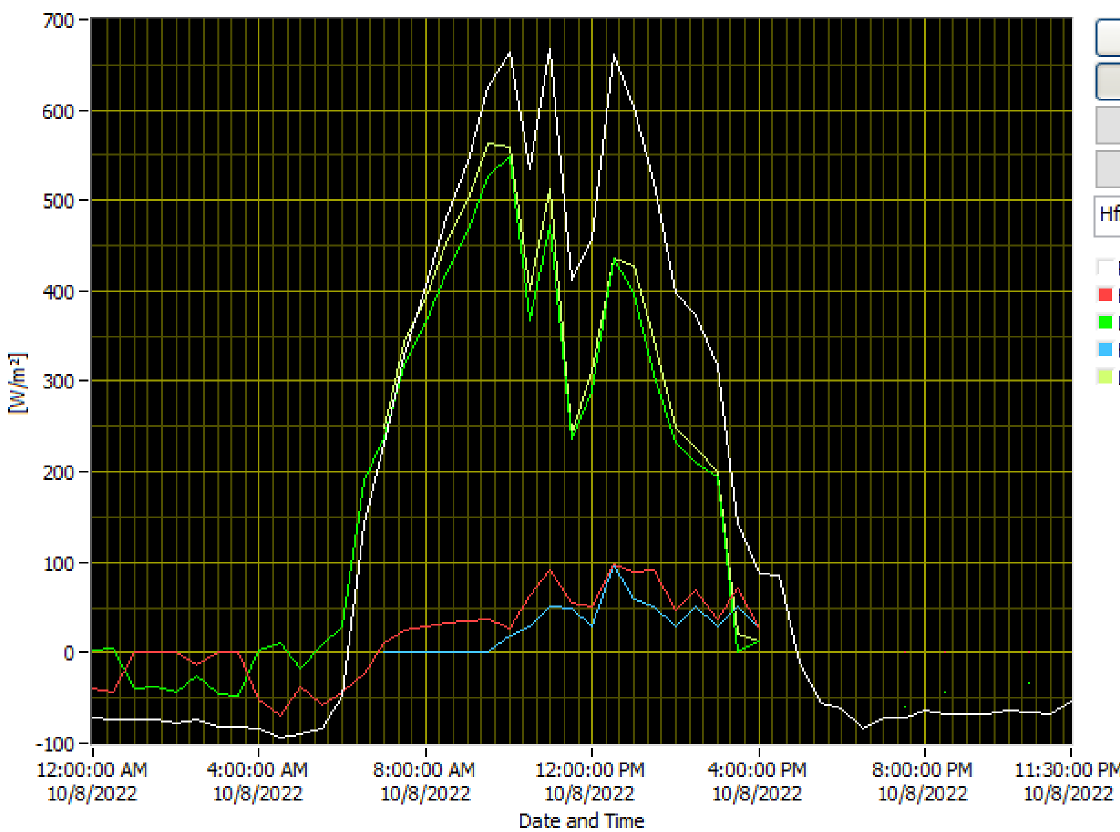

Figure 5-30 Example of output from Evation for 08/10/2022 to show the range of output from the LAS. Latent heat of evaporation (LvE) is used to calculate daily ET.

Daily variation in radiation (Rn), sensible heat (H, Hfree) and latent heat (LvE, LvEfree) over the planting of *C. sativa* in the cropping area (Figure 5-31). The data was measured on the 2nd of January 2023 when the plants were 16 weeks old and had been in the cropping area for two months. The pattern of increasing LvE with increasing radiation can be observed in this figure. The highest LvE value measured after *C. sativa* had been planted is approximately 550 W/m^2 which is the same LvE value measured when grass was growing in the cropping area. The highest radiation measured was 850 W/m^2. All the other parameters followed a similar trend of increase with increasing radiation.

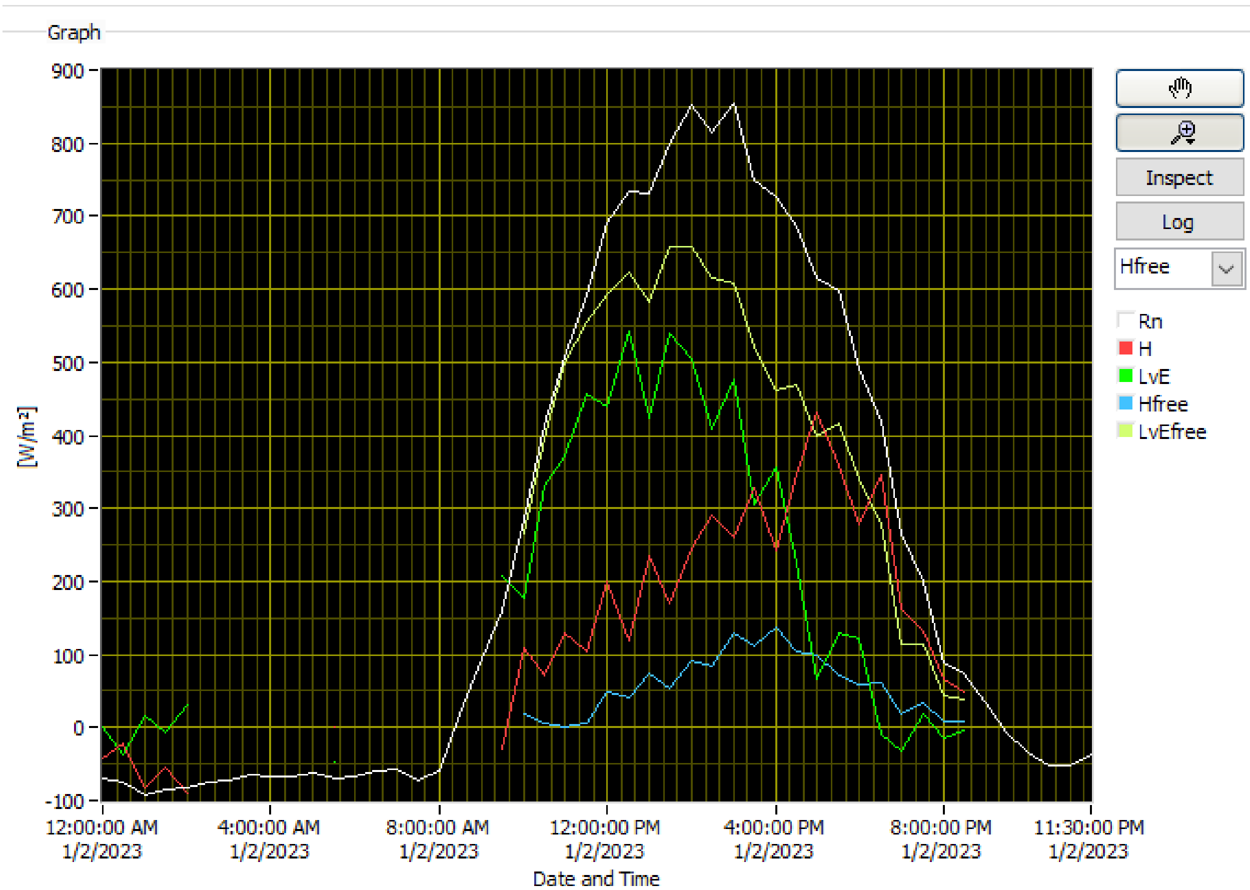

Figure 5-31 Evation output graph illustrating ET at 20-minute intervals after Cannabis sativa has been planted

The daily ET of 08 October 2022 and 02 January 2023 is shown in Figure 5-32. This figure compares the two LvE, the 8th October is the LvE of *E. plana* grass while the 2 January is *C. sativa*. The two LvEs follow a similar trend and the same maximum LvE which is 550 W/m^2 despite these similarities the times when the maximum is reached are different. *E. plana* reached its maximum between 9:30 and 10:00 in the morning while the maximum LvE for *C. sativa* was reached between 12: 00 and 12:30 midday.

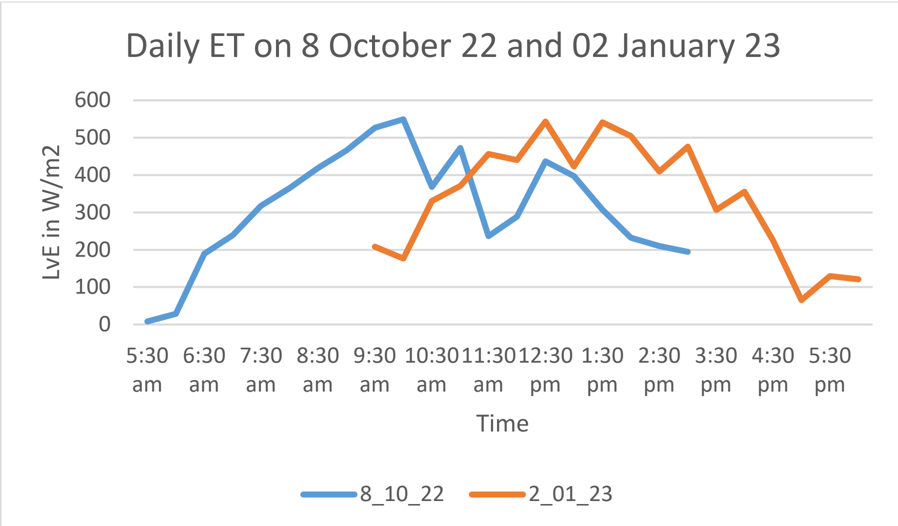

Figure 5-32 Daily ET comparison between 8 October 2022 and 2 January 2023

5.10 Soil

The majority of plants need soil as a growing medium, therefore there is a relationship that exists between soil and plants (Pessakli, 1999). Soil samples were obtained in order to investigate what kind of relationship exists between soils in Firglen and *C. sativa*.

The analysed soil samples were obtained from Firglen study site. The samples were collected on-mounds and off-mounds. The soils collected on mounds exhibited higher values for nutrients such as Potassium (K), calcium (Ca), Magnesium (Mg) and Zinc but phosphorus was higher on off-mound (Table 5-7). The pH was higher on-mounds when compared to off-mounds showing that the soils of the abandoned cultivated lands were more acidic than the contours or mounds. Despite on-mounds having higher pH, the soils in Firglen are acidic in nature. The total cation exchange was higher in on-mounds compared to off-mounds while the density was similar. There is an overall significant difference between nutrient levels found on the two areas ($p < 0.001$).

Table 5-7 Descriptive statistics of soil nutrients at Firglen

Nutrients	On-Mound		Off-Mound	
	Mean	**Standard deviation**	**Mean**	**Standard deviation**
Phosphorus (P)	6	1	7	2.64
Potassium (K)	203	20.88	136	12.28
Calcium (Ca)	2315.67	320.83	1306.33	296.42
Magnesium (Mg)	309	33.28	243.67	24.42
pH	5.24	0.07	4.37	0.4
Zinc (Zn)	2	0.34	1.96	1.97
Total Cation Exchange	14.72	1.8	9.09	1.4
Sample Density	1.17	0.01	1.18	0.01

5.11 Meteorological attributes of Firglen

Stomatal conductance decreases as the summer months give way to the winter months, this occurs due to the drop in temperature and radiation which are one of the major drivers of evapotranspiration (Allen, 1998). This observation corroborates the findings of Allen (1998) whereby the model used to measure evapotranspiration which is the derivative of the Penman-Monteith uses temperature and radiation among other parameters to measure evapotranspiration.

When bergwind conditions occur, the *Cannabis* crop is threatened by excessively high air temperature, high wind speed and low soil moisture. These events are common in the Eastern Cape Province and have resulted in previous *Cannabis* crop failure in dryland cultivation (Palmer, personal communication, 2022). The first crop failure at Firglen in 2022 coincided with these severe weather conditions which are high wind speed and high temperatures, which are the key drivers of evapotranspiration. These abiotic factors play a significant role in the growth and survivorship of *C. sativa* and it is therefore imperative that growers choose areas that will minimize the effects of these factors. Farmers should employ different methods such as covering the crop with cloches, irrigate the crop regularly and create wind breaks (Brandle et al., 2004). Brandle et al. (2004) further argues the importance of wind breaks and how they aid in the protection of crops from wind. The risk of total crop failure in dryland cropping can be avoided if short-term supplementary irrigation, such as that provided at Firglen, is available.

The higher mean ET observed in *C. sativa* compared to *E. plana* is due to *C. sativa* having a higher leaf area index when compared to *E. plana* (Figure 5-33). It has been observed in the study that less healthy plants or plants under severe stress had higher stomatal conductance. We suggest that these plants are dying and are unable to exercise any stomatal control.

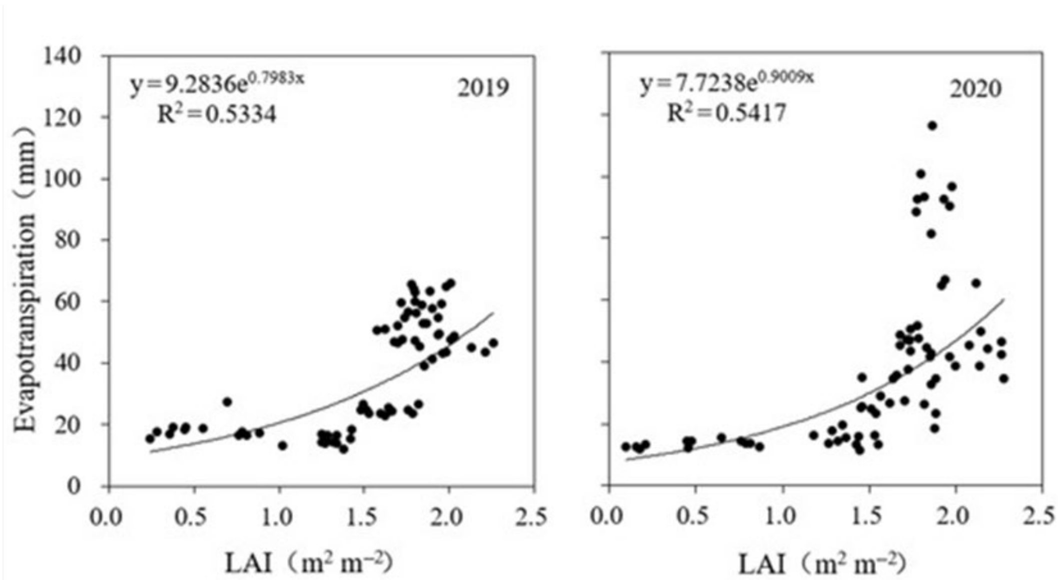

Figure 5-33 The relationship between evapotranspiration and leaf area index taken from Jia and Wang 2021

5.11.1 Wind speed

Wind speed is one of the parameters or factors that play a significant role in the rate of evapotranspiration. This is due to the fact that higher wind speeds lead to higher evapotranspiration rates (Tolk et al., 2006). The average wind speed that could lead to excessive evapotranspiration rate is between 2 to 4.4 m sec-^{1} (Tolk et al., 2006). The plants at Firglen were regularly exposed to wind speeds in excess of 2 m sec-^{1} and in some days the wind speed went up as high as 14 m sec-^{1}. This explains the high stomatal conductance observed in the *C. sativa* plants, in addition these high wind speeds have led to some physical damage to plants thus reducing the plant's ability to exercise optimal stomatal control due to their compromised physiological state. It is therefore imperative that growers take into account the wind speed of the area they want to cultivate especially in semi-arid environments because high wind speed coupled with dry high temperatures could lead to crop failure, and growers are strongly encouraged to plant windbreaks of Napier fodder (*Pennisetum purpureum*) or some other appropriate, non-invasive species.

5.11.2 Soil moisture

The highest soil moisture was recorded in the months of November and December which coincide with the rain season in large parts of the Eastern Cape which has summer rainfall. April and May also had high soil moisture content even though these months had a lower rainfall when compared to November and December, this can be attributed to increased irrigation frequency after it was observed in February and March 2022 that the plants started to die off due to lack of rainfall and reduced irrigation which ultimately led to decreased soil moisture content. February is one of the months that exhibited the lowest soil moisture content, this was due to an unusually very dry January and February with high temperatures. The plant mortality was also compounded by the limited irrigation from our side because we also wanted to observe if these plants can survive such conditions without significant input i.e., irrigation. This was done to mimic the conditions that are prevalent rural growers across Eastern Cape since these growers rarely have irrigation systems in place due to financial constraints and the previous legal status of *C. sativa.* This experiment was unsuccessful, and our findings suggest that *C. sativa* needs significant amounts of water in order to survive and ultimately thrive. A soil moisture of about 23% is ideal for *C. sativa* cultivation. The study site had an average soil moisture content of about 17% which is below the ideal soil moisture content needed for optimal growth of *C. sativa.*

It is therefore important that the soil moisture content is kept at 23% in order to for *C. sativa* cultivation to be successful. There are cost effective and sustainable ways of irrigating crops that could be adopted by small scale rural growers such as the drip irrigation system that was utilised in our study site. Another way is the setting up of fog harvesters in these locations, fog harvesting sustainable with minimal environmental impact. These methods can aid in alleviating the stress exerted on the water supply of the Eastern Cape and South Africa as a whole.

5.12 Stomatal conductance and other measured parameters

In this sub-chapter stomatal conductance measured in 2022 to 2023 of both *E. plana* and *C. sativa* will be discussed and analysed.

5.12.1 Stomatal conductance first trial early to mid-2022

The first trial involved measuring the g_s of the local grass which is *E. plana* and *C. sativa.* The obtained results show that *C. sativa* has an overall higher g_s when compared to *E. plana.* This difference can be attributed to the physiological differences of these two plant species especially their leaf sizes (Franks et al., 2009). *C. sativa* has a larger leaf surface area when compared to *E. plana* which means that there is high number of stomata on the surface of *C.* sativa leaf thus facilitating greater ET which results in higher stomatal conductance when compared to *E. plana* (Franks et al., 2009). The Month of April exhibited the lowest g_s when compared to the other months where measurements were taken, this is due to the lower average temperatures observed in April when compared to March and May. A similar trend with wind speed was observed whereby April had lower wind speeds when compared to the other two months. These findings further corroborate the works of Allen et al. (1998) which suggests that windspeed and temperatures are one of the main drivers of ET. Evapotranspiration and stomatal conductance are linked and have a positive correlation as observed in the study conducted in both Firglen. In the study site some plants that had very high g_s had a higher mortality rate due to loosing large amounts of water through evapotranspiration. Which further confirms the relationship between g_s and ET.

5.12.2 Stomatal conductance late 2022 to 2023

The stomatal conductance measured from December 2022 to March 2023 reveal a similar trend to what was observed from earlier data collection periods. The trend is decreasing stomatal conductance as the summer months of December and January give way to autumn months like March. The 9th of December had one of the highest g_s while the 2nd of March had the lowest average g_s. This further confirms the findings that suggest that temperature is one of the leading drivers of g_s and subsequently ET since December is the height of summer and March is when the temperatures gradually start to decrease.

5.12.3 Stomatal conductance in Firglen and Sweetwaters Tunnel Facility

In this section stomatal conductance in both study sites will be discussed and conclusions will be drawn.

In Firglen the healthier plants in section B, C and D have constantly exhibited high stomatal conductance with exception of section A which is less healthy but exhibits very high stomatal conductance, this is exhibited in the January data. In February section E which has the unhealthiest plants, exhibited the highest stomatal conductance. The high stomatal conductance observed in unhealthy plants such as those found in A and E can be attributed to the fact that these plants practice little to no stomatal control due to being under severe stress, lack of nutrients and acidic soils (Desai, 1939).

The aquaponics treatment exhibited the highest stomatal conductance when compared to other tunnel grown plants viz, bags and soil. This can be attributed the amount of water the plants under this treatment receive which is significantly higher (submerged in water) when compared to the other two treatments bags and soil which receive 2.5 litres a day and 4 litres per day when temperatures are high. It can therefore be deduced that there is a strong correlation between the amount of water a plant receives and the stomatal conductance because when water is plentiful plants can afford to keep their stomata open in order to facilitate photosynthesis (Farquhar and Sharkey, 1982, Damour et al., 2010). Despite all this, the plants grown in the outdoor farming area at Firglen exhibited higher g_s when compared to those grown in tunnels. This can be attributed to the fact that the outdoor grown plants are exposed to meteorological elements such as high temperatures and high wind speeds that facilitate ET thus resulting in higher g_s. *Cannabis sativa* plants that receive plentiful water are usually healthier than those who are water stressed because plants are able to perform at optimum level and processes like photosynthesis are also working at optimum level as well. This can be clearly observed at Firglen whereby water stressed plants exhibited signs of being unhealthy (brown and yellow leaves)

Our study corroborates the findings of Dills et al. (2020) where it was mentioned that indoor facilities use significantly more water when compared to outdoors. In our study the outdoor farming used a drip irrigation (2 litres on hot days) while the tunnel facility used 5 litres on bags and 4 litres in soil while the plants in aquaponics were submerged in water.

5.12.4 Leaf Area Index

Leaf area index (LAI) can be defined as a variable in botany or plant science that is used to describe the amount of leaf area in a particular landscape (Breda, 2003). It helps researchers to better understand the plant's photosynthetic abilities and also help determine the water and nutrient requirements of the plants (Breda, 2003). A high LAI indicates that a plant is healthy since its photosynthetic activity is high which ultimately leads to better productivity and growth (Breda, 2003). In the study at Firglen LAI was observed to be initially higher in plants growing of section B, C and D which where areas that had fertilizer applied or growing on contours/mounds which are areas of higher nutrients. Despite this initial trend of plants in these areas having higher LAI than A and E, as time progressed it was observed that the plants in section E which were less healthy when compared to the rest exhibited higher LAI especially in March. This apparent new trend of high LAI in section E could be explained by the method at which LAI is calculated by ceptometer. Ceptometer measures above and below canopy photosynthetically active radiation and calculates

LAI as a ratio of the two (Pokovai and Fodor, 2019). In the case of E, the difference between above canopy and below was not as significant as the other sections thus leading to much higher LAI. Another explanation to this anomaly could be attributed to variability, the plants measured in March could be different from the ones measured in earlier months thus giving rise to this new observation.

The LAI is a good indicator of a plant's growth and health, but it can also be misleading if other parameters are not considered. For example, plants in section E exhibit high LAI but all the other parameters such as height, width and chlorophyll content are significantly low than other sections and also, they have an extremely high stomatal conductance signaling that they do not exercise any stomatal control. It is therefore imperative that a holistic approach is applied when looking at a plant or crops performance and health and consider all the other parameters.

5.12.5 Height and Width

The height and width of a plant is one the parameters that show that a plant is growing and is healthy. The plants in Firglen progressively grew during the cropping period, the healthy plants in section B and D grew to heights of between 1.6 and 1.8 m and widths of about 0.8 and 1.2 m with some plants reaching 2 m in height and 1.3 m in width. These observed heights and widths in these sections could be attributed to the fertilizer applied and planting on mounds. This further illustrates the importance of nutrient rich soils for *C. sativa.* This is stark contrast to the notion that *C. sativa* does not need any input in the form of fertilizer in order to grow successfully. It is therefore important for farmers to plant the crop in fertile soil or apply fertilizer. In the case of legacy farmers in the Eastern Cape it is advised that organic fertilizers such cow dung (umgquba) should be used to increase the nutrient content of the soil.

5.13 In-trial fertilizer application

A TukeyHSD was performed and it revealed that there was no significant difference in g_s between all the different treatments. It can therefore be concluded that the porometer is insensitive to quite large differences in plant growth conditions, and that a single value of g_s can be calculated using all the readings on each day. The other parameters such as width, height and LAI all had significant difference between the different treatments. The significant difference in all the parameters were observed between the tall healthy plants from treatment (B and D) and less healthy plants from treatments (E and A) as observed in Tables 5-3 and 5-4. These findings corroborate what is observed in the cropping area whereby these differences in physical appearance can be seen and whereby plants from A and E which were short, wilting and unhealthy compared to tall and healthy plants of B and D. These observed differences are a result of lack of nutrients and low pH in treatment A and E when compared to the other three treatments. It should be noted that treatment A had fertilizer applied but it still produced less healthy plants, this can only mean that the soils in A were extremely nutrient deficient as compared to other sections of the cropping area and even after the application of fertilizer it was still not sufficient for plants to grow into healthy crops. The B and D sections mostly did not have any significant difference between them except for leaf area index and width on the 8th of March, this can possible be attributed to measurement precision and not to nutrient availability and pH in the soil.

5.14.4 Evapotranspiration Model

The Evation model illustrates the relationship between radiation and evapotranspiration, from the model it can clearly be observed that there is a positive correlation between these two parameters. An increase in radiation leads to an increase in evapotranspiration and the increases occur during the day which further confirms that radiation and temperature are the two main driving forces of ET. These findings corroborate the findings made when g_s was measured as a proxy for ET using a hand-held leaf porometer. This further confirms that radiation and temperature are the main drivers of ET. The values of LvE which is used to measure ET of *C. sativa* were the same with those measured for *E. plana*. This is in stark contrast to the g_s data whereby *C. sativa* had significantly higher g_s values when compared to *E. plana.* This difference could be attributed to the fact that the 8th of October had higher temperatures when compared to the 2nd of January. The reason for the difference in stomatal conductance could be attributed to the size and density of stomata of the two different plants with *E. plana* having smaller size and less density than *C. sativa* (Franks et al., 2009).

There is a positive correlation between soil moisture and the rate of evapotranspiration; this can be clearly since in Figure 5-29. The data is from October 2022, the daily ET of *E. plana* and soil moisture show a positive correlation between the two, i.e., an increase in soil moisture directly leads to an increase in in daily ET. This finding is corroborated by Morills et al. (2013) whereby it was discovered that when soil is saturated after a rainfall event this results in increased ET. This phenomenon has been observed at Firglen at various times after a rainfall event. It is therefore imperative that researchers take cognisance of this so that models do not overestimate ET. Models need to be rigorously tested in order to get the one that mostly accurately predicts the observed ET.

5.15 Firglen Physical Attributes

5.15.1 Soil

Soil and plants have an inseparable relationship because plants need soil as a medium to grow in and also need the nutrients that the soil provides (Pessarakli and Szabolc, 1999). The nutrients and the type of soils can be a determining factor if certain plants or crops will survive and flourish or fail in certain in environment (Pessarakli and Szabolc, 1999). Soil nutrients such as calcium, potassium, phosphorus and nitrogen are essential for plant growth and continued survivorship (Pessarakli and Szabolc, 1999). Plants extract these minerals from the soil for their growth and survivorship and if the soil is not given time replenish these nutrients due to inadequate land management, this could lead to nutrient deficiency. The soils at Firglen exhibit signs of nutrient deficiency due to past land management practices. In this chapter we will look this relationship between soil nutrients and the effects they have on the plants, i.e. *C. sativa.*

Cannabis sativa plants in section A are one of the shortest plants measured and their leaf area index was one of the lowest until March, yet their stomatal conductance was one of the highest. This is in stark contrast to the other plants found in different sections of the cropping area, for example the plants in section B and D had one of the tallest plants, highest stomatal conductance and highest LAI values. This difference exhibited by section A can be attributed to the fact that these plants are under severe stress due to the acidic nature of the soil in that section and nutrient deficiency (Desai, 1939; Pessarakli and Szabolc, 1999). This has led to the plants to exercise very little stomatal control. The plants growing in section B and D are among the healthiest and have high values for LAI, g_s, height and width. This could be attributed to their growing locations, these plants grow on mounds and a previous study done in the area has shown that the nutrient levels on the mounds are much higher when compared to off-mounds (Palmer and Mantel, 2018). The higher nutrient levels on the mounds are due to organic material and topsoil that was moved from other areas to create the mounds or contour banks approximately 50 years ago. The higher organic material on the mounds has resulted in taller, healthier and bigger plants when compared to the plants grown in the flat cropping area. The height of plants growing in section C exhibited exponential growth between the 3rd and 26th. This exponential growth could be attributed to the fertilizer (organic NPK) that was applied in the section towards the end of 2022. Higher nutrient levels in the soil aid in the growth of *C. sativa* because the plants in section E were the shortest and overall, less healthy than the other treatments and these plants in E did not receive any nutrients. Plants growing in section D also did not receive any fertilizer but because they were growing on mounds, they were able to receive sufficient nutrients in order for them to grow into healthy plants.

Nutrients such as potassium, phosphorus, magnesium and calcium are essential for plant growth (Desai, 1939; Pessarakli and Szabolcs 1999). In the study, section B and D had much higher K, Mg and Ca when compared to A, C and E which could be the reason why the plants in B and D were significantly taller and bigger. Despite the high K, Mg and Ca in B and D, P was lower in B and D when compared to A, C and E. This did not have a major impact since the P levels in A, C and E did not differ significantly to P levels in B and D. This finding shows that high P level alone will not yield bigger and taller plants. More nutrients are needed for *C. sativa* to grow optimally in dryland area like the Eastern Cape. A similar phenomenon was observed at Firglen study site, the soils at the site are mostly sandy and have poor water retention which led to wilting and subsequent plant mortality.

5.16 Parametrisation

5.16.1 Comparing C. sativa and E. plana Models

This section will involve the discussion of how accurately the MEDRUSH model predicts the actual ET. In our research actual ET means the ET that is obtained from the Large Aperture Scintillometer (LAS) at Firglen study site. It also looks at how MEDRUSH model predicts actual ET for *E. plana* and *C. sativa*.

Model performance was evaluated using the root mean square (RMSE), RMSE-observations standard deviation ratio (RSR), mean absolute error (MAE) and the percent bias (PBIAS) and these were calculated as follows:

$RMSE$= [N−1Σ (Pi−$Oini$=1)2]0.5 [5.1]

$MAE = N-1\Sigma|\ Pi-\ Oi|ni=1$ [5.2]

$RSR = RMSESTDEVobs =$ [$\sqrt{}\Sigma$ $(Oi-\ Pi)2ni=1$] [$\sqrt{}\Sigma$ $(Oi-\ Pi)2ni=1$] [5.3]

$PBIAS = \Sigma\ (Oi-\ Pi)\ ni=1*$ (100) $\Sigma(Oi)ni=1$ [5.4]

where Pi is predicted and Oi is observed ET and $STDEVobs$ is standard deviation of the observed ET.

The RMSE indicates a perfect match between observed and predicted values when it equals 0 (zero) and higher values are indicative of poor match. To illuminate the sources or types of error in the RMSE, the mean square error (MSE) was decomposed into systematic and unsystematic MSE (Willmott, 1981). Systematic MSE is given by:

$MSEs = N-1\Sigma\ (Pi-Oini=1)2$ [5.5]

where $MSEs$ is systematic MSE, Oi is observed ET and Pi is derived from $Pi=a+bOi$, i.e., the linear regression between the observed and modelled ET. The unsystematic MSE is expressed as:

$MSEu = N-1\Sigma\ (Pi-ni=1\ Pi)2$ [5.6]

Subsequently, the systematic and unsystematic RMSE were calculated and the respective proportions of these were determined as a percentage of the observed mean ET.

The MAE was used since it is less sensitive to extreme values than RMSE and it avoids the considerable artificial exponentiation that is indicative of statistical mathematical reasoning from which RMSE comes from (Moriasi et al., 2007). The RSR is also a valuable index since it helps to give insights as to a measure of what is considered a lower RMSE since RSR closer to zero indicates low RMSE and suggests better model simulation (Moriasi et al., 2007). Further to these the coefficient of determination (R2) and the slope and y-intercepts were investigated. The R2 ranges between 0 and 1 and it denotes the proportion of the variance in the measured data, which is explained by the model, with higher values indicating less error variance. A slope of 1 and intercept of 0 (zero) indicate good model fit and the opposite is true. PBIAS was also considered in order to determine the tendency of predicted values to be greater or smaller than the observed ET values.

The lower MAE, RMSE and RSR observed in *E. plana* indicate that the model was accurate at predicting the actual ET measured by the LAS. It can also be observed that the model for *E. plana* was better at predicting daily ET when compared to MEDRUSH 10 which is *C. sativa*. Despite *C. sativa* having higher MAE, RMSE and RSR values than *E. plana* its values are still small enough that it can be deduced that the model was relatively accurate at predicting the actual daily ET.

5.16.2 Model Evaluation in different days

The model was able to accurately predict the actual LAS ET on three days viz; 29 December 2022, 14 December 2022 and 5 December 2022, these days had the lowest values for performance metrics such as MAE, RMSE and RSR which indicates that the model was accurate at predicting the actual ET. The PBIAS was negative on all these three days which means the predicted values are lower than the observed values (LAS). Despite the fact that model was able to accurately predict ET for the above-mentioned days it could not accurately predict the actual ET on the 3rd of January 2023, 8th of October 2022 and on the 2nd of January 2023 because the values of MAE, RMSE and RSR were large and that signifies that the model did not accurately predict the actual ET. The PBIAS values were positive which means the predicted values were larger than the observed values. This observation could be a result of the weather station not operating at optimum level due to disruption in the previous days as a result of network disruption and data capture was therefore hindered. This assertion is backed by the fact that the other three days which include 29 November 2022, 28 December and 7 January 2023 did not exhibit high values for all the error metrics which signifies that the model can relatively predict the actual ET accurately because out of nine days, six of those days the model was able to accurately predict the actual ET. The daily ET was the highest on the 22nd of December 2022. The lowest ET was measured on the 5th of January 2023, this was of one the days were the model performed relatively well in predicting the ET. It can therefore be deduced that these ET values represent the observed ET values from LAS, further confirming the accuracy of the model at predicting the observed or actual LAS ET.

The model is ideal because it is able to perform well with only a few meteorological parameters viz; air temperature, relative humidity, wind speed, soil temperature and radiation. This means it could be adapted and used in almost every landscape or biome across the globe and it is well suitable for the global South where there is paucity in data and also financial constraints since eddy covariance and scintillometers are expensive to purchase and maintain.

5.17 Conclusion

The main aim of this research was to investigate and better understand the water use of *C. sativa* in order to make informed decisions about its cultivation under commercialized dryland conditions in south Eastern regions of South Africa. Data were collected from two sites in the Eastern Cape Province for a period of about 18 months. The main aim and objectives of this project were achieved in that we now have a better understanding of the water use *C. sativa* and the ideal environment to grow it in order to obtain optimum yield.

In line with objective one, we successfully planted a crop of *C. sativa* under dryland conditions that mimicked the type of agronomic practices that legacy farmers in the Eastern Cape and KZN could apply. We encountered a number of challenges while executing this objective. The first major obstacle that we encountered initially was poor germination of seeds due to the type of soil that was used. The local soils which were used were not appropriate for germinating seeds because they easily became compact and hard making it difficult for seeds to germinate. The soils were also studied previously, and it was discovered that they were nutrient deficient and of very low pH. Small-scale Cannabis farmers would need to be trained to germinate seeds in the correct environment. We managed to overcome these obstacles by mixing the soil with cannabis soil mixture, potting soil, powder feeding and vermiculite (magnesium-aluminium-iron silicate). The seeds germinated after we employed this method. The seedlings were hardened before transplanting into the cropping area to achieve our first objective, but plant mortality was extremely high leading to crop failure due to a combination of climatic events such as extremely high temperatures and bergwinds and soil properties. We changed the planting period to November instead of February. A drip irrigation system was installed in order to avoid wilting and eventual plant mortality. All these remedial actions helped achieve the first objective. More 90% of the plants grew to maturity and were harvested with a yield of 4202 g of good quality *C. sativa* and 712g of less than optimum quality. This further proves the importance of water availability, nutrients and correct planting period. These factors should always be taken into consideration when embarking on a project of this nature. These findings are in stark contrast with the popular belief that *C. sativa* can grow anywhere and without any input in the form of fertilizer or irrigation. In a study conducted in Mpondoland region of the Eastern Cape, Højgaard (2021) discovered that the farmers used fertilizer on their crops. The majority of these farmers used cow dung as fertilizer while a minority used chemical fertilizers. The farmers also watered their plants regularly especially when growing the high-grade strains (Højgaard, 2021). It should be noted that Mpondoland, unlike the Makhanda area, falls in the eastern portion of the Eastern Cape and receives more rain than the western side of the province where Makhanda is located (Mahlalela, 2020). Despite this the farmers saw the need to water their plants in order to obtain the ideal plant. This corroborates findings from our study at both Firglen and across the globe that suggest that *C. sativa* needs regular irrigation or water supply for its survival (Lisson, 1998). Despites these findings, Amaducci et al. (2015) indicates that certain varieties of *C. sativa* like Futura 75 can survive in environments with reduced water supply. This proves the importance of choosing the correct variant for that particular environment.

We measured the rate of evapotranspiration from a cover of *C. sativa* using a large aperture scintillometer in a dryland location. This objective was achieved but a number of obstacles were encountered and eventually overcame. The LAS system was installed in a farming area and from time-to-time cattle would collide with it leading to the slight shift of the antenna and this led to gaps in the data. An electric fence was erected to prevent this from happening. The results we obtained revealed that the ET measured by the LAS was similar to what was obtained from the MEDRUSH model. The average measured daily ET for *C. sativa* at Firglen study site from November 2022 to January 2023 was 1.76 mm while the daily ET of tomatoes measured over a period of 10 days was constantly above 5 mm (Allen et al., 1998). This further shows that the *C. sativa* variety grown at Firglen may not be as water thirsty as other plants or varieties grown in the northern hemisphere such as the ones described by Dills et al. (2020) in northern California.

We parameterized and validated a transpiration model (MEDRUSH) that can be used to simulate water use at other sites. This objective was also achieved but we did not face many physical challenges. The major challenges were technical and were all eventually overcame. The MEDRUSH model was able to accurately predict the actual ET of *C. sativa* measured by LAS. This is evidenced by the minimal difference between observed daily mean ET which is 1.76 mm and the predicted mean ET which is 2.52 mm meaning the difference in this case is 0.76 mm.

We measured stomatal conductance under a range of growth and environmental conditions. Stomatal conductance was measured in both Firglen and Sweetwaters Tunnel Facility. The major challenge in achieving this objective was also technical, the leaf porometer had problems of configuration but after several trials we managed to make it work optimally and we were able to obtain stomatal conductance data. That was a vital component in the MEDRUSH model. The results revealed that the less healthy plants had higher stomatal conductance due to the fact that they are unable to exercise stomatal control and end up losing a substantial amount of water leading to their poor health and eventual mortality.

The plants grown under tunnel conditions also exhibited high stomatal conductance but unlike the unhealthy plants in Firglen, these plants were healthy and only had high g_s due to the amount of water they were receiving. This is due to the positive correlation that exists between the amount of water and g_s in healthy plants.

These results reveal that *C. sativa* can be grown commercially in a dryland location. These results further reveal that commercial farming can be achieved inexpensively because the plant needs minimal input in order to achieve the best results. The major inputs include water, irrigating the plants with the use of drip irrigation, this has proven to be great tool in using water sparingly and it also yields great results. The second input is fertilizer, this could be natural fertilizer like cow dung or organic liquid fertilizer (NPK). These results also reveal that the MEDRUSH model can be used in other locations and yield reliable ET data.

5.18 References

BOOTH S (2022) Personal communication. Manager, Sweetwaters Cannabis Facility.

BUTTNER SH, STEPHEN AP AND GESS R (2015) Field guide to geological sights of Grahamstown. Rhodes University Department of Geology.

COSENTINO SL, TESTA G, SCORDIA D, AND COPANI V (2012) Sowing time and prediction of flowering of different hemp (*Cannabis sativa* L.) genotypes in southern Europe. Industrial Crops and Products **37**(1) 20–33. https://doi.org/10.1016/j.indcrop.2011.11.017

DE LACY P AND SHACKLETON CM (2017) Woody plant species richness, composition and structure in urban sacred sites, Grahamstown, South Africa. Urban Ecosystems **20**, 1169-1179.

DOORENBOS J AND PRUITT WO (1977) Guidelines for predicting crop water requirements. FAO Irrigation and Drainage Paper 24. Food and Agriculture Organization, Rome.

DU PREEZ A (2023) Personal communication Nguni cattle farmer at Firglen farm.

ESAU K (1977) Anatomy of Seed Plants. Wiley and Sons. p. 88. ISBN 978-0-471-24520-9.

EVANS FJ (1998) Palaeobiology of early Carboniferous lacustrine biota of the Waaipoort formation (Witteberg group), South Africa.

FONTENOT RL (2004) An evaluation of reference evapotranspiration models in Louisiana. MSc Thesis, Louisiana State University, Baton Rouge. 3 pp.

GIMENEZ C, GALLARDO M AND THOMPSON RB (2005) Plant–water relations. In: Hillel, D. (ed.) Encyclopedia of Soils in the Environment. Academic Press 231-234.

HEMAKUMARA HM, CHANDRAPALA L, MOENE AF (2003) Evapotranspiration fluxes over mixed vegetation areas measured from large aperture scintillometer. Agricultural water management, 109-122.

HOARE DB, MUNCINA L, RUTHFORD MC, VLOK JHJ, EUSTON-BROWN DIW, PALMER AR, POWRIE LW, LECHEMERE-OERTEL RG, PROCHES SM, DOLD AP AND WARD RA (2006) Subtropical Thicket Biome **10**, 542-560.

KIPP AND ZONEN (2021) LAS MkII Instruction Manual. Netherlands.

LOCK BE (1974) The geology of the Eastern Cape. Grahamstown and its Environs.

MCCONNACHIE MM, SHACKLETON CM AND MCGREGOR GK (2008) The extent of public green space and alien plant species in ten small towns of the subtropical thicket biome, South Africa. Urb for Urb Green **7** 1-13.

METER GROUP (2022) https://www.metergroup.com/en/meter-environment/products/sc-1-leaf-porometer-stomatal-conductance

OSBORNE CP AND WOODWARD FI (1999) The MEDRUSH Vegetation Model.

PALMER A (2022) Personal communication Professor Institute of Water Research, Rhodes University. Makhanda rainfall data form various stations.

SAWLER J, STOUT JM, GARDNER KM, HUDSON D, VIDMAR J, BUTLER L, et al. (2015) The Genetic Structure of Marijuana and Hemp. PLoS ONE **10**(8), e0133292. https://doi.org/10.1371/journal.pone.0133292.

SCHULZE RE (2007) South African Atlas of Climatology and Agrohydrology. In Water Research Commission report 1489/1/06.

SNYMAN HA (1999) Short-term effects of soil water, defoliation and rangeland condition on productivity of a semi-arid rangeland in South Africa. Journal of Arid Environments **43** 47 - 62.

SOUTH AFRICAN HISTORY ONLINE (2023) Sahistory.org.za/place/grahamstown.

STANCALIE G AND NERTAN A (2012) Possibilities of deriving crop evapotranspiration from satellite data with the integration of other sources of information. National Meteorological Administration **97**.

SWARTHOUT D AND HOGAN CM (2010) Stomata. Encyclopaedia of Earth. National Council for Science and the Environment, Washington DC.

THOMAS B, MURRAY BG, MURPHY DJ (2017) Encyclopaedia of Applied Plant Sciences. Second Edition. Imprint Academic press.

TROUNG N (2012) Quantifying evapotranspiration through a sensitivity study of climate factors and water table interactions for a constructed wetland mesocosm. MSc Thesis, Villanova University, The Graduate School Department of Civil and Environmental Engineering.

UNITED STATES GEOLOGICAL SURVEY (2012) Estimation of evaporation from open water- A review of selected studies, Summary of U.S Army Corps of engineer's data collection and methods for estimation of evaporation from five reservoirs in Texas.

CHAPTER 6 HYDROLOGICAL MODELLING AND IMPACTS

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This chapter provides the background to the modelling activities, with Section 6.1 focusing on the crop modelling using AquaCrop, whilst Section 6.2 focuses on the hydrological modelling. This chapter is linked to aim 4 of the project, i.e. modelling the water use, yield and potential hydrological impacts of *C. sativa*.

6.1 Crop modelling

6.1.1 Introduction

Cannabis plants are generally dioecious meaning that male and female reproductive organs are found on separate plants. However, sometimes cannabis plants demonstrate intersex characteristics and are referred to as hermies. Monoecious varieties have both male and female flowers development on the same plant. Only female plants can produce floral buds that are harvested for cannabis oil, typically for medicinal use only. Hence, male plants and hermies must be removed before the flowers open to prevent pollination and seed development since pollination can reduce oil yield by 56% (Meiner and Mediavilla, 1998). When the male or dual-sex plants are not removed, they pollinate the female plants, which results in seed production and reduced bud harvest. Male plants die shortly after flowering.

During the pre-flowering phase, male or dual-sex plants produce flowers about two weeks before female flowers, which then produce pollen. Wind pollination from male to neighbouring female flowering plants is dominant since female flowers do not attract bees. This means that hemp grown for seed can inadvertently pollinate hemp grown for bud yield, unless the two fields are more than 16 km apart (DeDecker, 2019). For oil production, the buds should be harvested when half of the trichome heads have turned from transparent to milky in colour, and the remaining trichomes have turned from milky to an opaque colour. Once the trichomes turn amber or brown in colour, or they begin to fall off, the plant has matured for too long. Dry bud mass is typically one-quarter of wet bud mass. Flowering takes a further 6-8 weeks to complete, which results in seed formation.

From the revised project proposal (called Annexure A), the original intention was to utilise measurements and observations obtained from the field and pot experiments conducted in KwaZulu-Natal and the Eastern Cape to partially calibrate the AquaCrop model. However, the experimental work focused on floral yield, where the buds were harvested before pollination took place, thus preventing seed development. Hence, feminised seed and clones were planted, and all male plants were manually removed to prevent pollination of female plants. These experiments represent the cultivation of *C. sativa* for medicinal use, where plants are typically grown on a small scale in greenhouses or fenced fields, and thus are unlikely to negatively impact downstream water availability.

Žydelis et al. (2022) reported few modelling applications of hemp, citing the use of APSIM (e.g. Lisson et al., 2000) and AquaCrop (Wimalasiri et al., 2021b). At the fourth Reference Group meeting held in April 2024, the decision was made to simulate both fibre and seed yield (not floral yield) using the crop parameter files originally developed by Wimalasiri et al. (2021b) for hemp. The water use of large-scale fibre (and biomass) production is more likely to reduce stream flow when compared to seed production since hemp is planted at twice the density.

6.1.2 Methodology

A detailed description of the AquaCrop model was provided by Kunz and Mabhaudhi (2023; cf. Section 2.1). For this project, a summarised version is provided next for the reader's convenience.

6.1.2.1 Model description

The AquaCrop model is developed and maintained by the Food and Agricultural Organisation or FAO (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2009). The previous version (v6) of the model was released in March 2017 with one new crop parameter file for dry bean (Raes et al., 2018). The latest version (v7) was released in August 2022 and has been successfully parameterised to simulate the growth, productivity and water use of 17 herbaceous crops (Raes et al., 2022), including cassava (Wellens et al., 2022) and alfalfa (Raes et al., 2023). The thoroughness of the parameterisation and validation process varies with each crop, which is discussed in the model's reference manual (Raes et al., 2022).

AquaCrop is a process-based water productivity model representing a simplified interpretation of water stress effects on crop productivity. The model has a water-driven growth engine (Steduto et al., 2009), and thus is particularly suited to simulating yield response to water availability, i.e. simulating yields affected by changing water availability and environmental conditions. The structural components of the model are shown schematically in Figure 6-1.

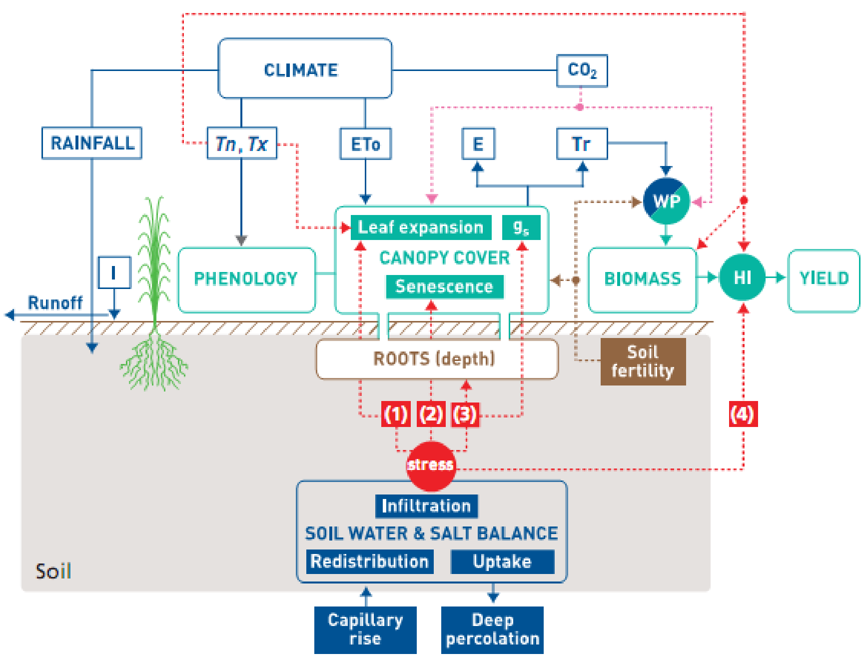

Figure 6-1 Structural components of AquaCrop, including stress responses and the functional linkages among them (Steduto et al., 2012)

AquaCrop requires inputs of (i) daily rainfall, maximum (*Tx*) and minimum (*Tn*) temperature, as well as reference crop evapotranspiration (ET_O). The latter is determined using the FAO56 (or Penman-Monteith) method described by Allen et al. (1998). In addition, the model requires annual CO_2 levels up to the present date, and decadal values into the future. The soil depth, soil water retention parameters (i.e. saturation, field capacity and permanent wilting point) and saturated hydraulic conductivity (K_{SAT}) are also needed for each soil horizon. AquaCrop can account for the effects of soil fertility and salinity on crop growth, as well as weed growth but not pests and diseases. AquaCrop simulates crop yield in four sequential steps as follows:

- First, canopy cover development is simulated, which affects, inter alia, the rate of crop evapotranspiration.
- AquaCrop utilises the dual crop coefficient method to calculate (i) crop transpiration (Tr) via the basal crop coefficient (K_{cb}), and (ii) soil water evaporation (E) via the K_e coefficient. This approach is especially useful during periods of incomplete ground cover when E is typically high. Since crop evapotranspiration is affected by soil water content, the model also simulates the following processes using a soil water balance approach: runoff (via the SCS-based method), infiltration into the topsoil, drainage out of the root zone (deep percolation) and capillary rise.
- AquaCrop then calculates biomass production (*B* in g m^{-2};) as the product of accumulated transpiration ($\sum Tr$ in mm) and the water productivity parameter (*WP*). The latter is an important crop-specific parameter that represents the biomass produced (g m^{-2} mm^{-1}) per unit of transpired water. To improve the model's robustness and applicability across different climates, *WP* is normalised by ET_O and the ambient CO_2 level, which is then called *WP**. This parameter behaves conservatively, remaining virtually constant over a range of environments, and is not affected by water stress (Steduto et al., 2009). *WP** is higher for C4 crops (typical range: 30-35 g m^{-2}) than C3 crops (typical range: 15-20 g m^{-2}) and is expected to increase over time due to anthropogenic increases in ambient CO_2 concentration.
- For most crops, only part of the biomass is partitioned to the harvested organs to give yield. Yield (*Y* in g m^{-2}) is therefore calculated from the product of biomass (*B*) and the harvest index (*HI*). The model requires another important input parameter called the reference harvest index (HI_O). When the model is run in growing degree-day (GDD) mode, *HI* is adjusted on a day-by-day basis over the yield formation period in response to temperature stress, which also enhances the robustness of the model. No other partitioning among the various plant organs occurs, thus avoiding the complexity of partitioning processes that are the most difficult to model (Steduto et al., 2009).

Based on the above, AquaCrop is sensitive to three crop-specific input parameters, namely K_{cb}, *WP* and* HI_O. AquaCrop accounts for various stress factors that affect crop growth. For example, plant stress due to a lack of soil water is governed by four stress coefficients related to canopy expansion, stomatal closure, early canopy senescence and aeration stress. These stress factors mainly affect leaf opening, canopy development, transpiration and stomatal control. Cold temperature stress reduces crop transpiration, whereas cold or hot temperature stress inhibits pollination and reduces HI (Steduto et al., 2009). It is important to note that temperature stress is only considered when AquaCrop is run in GDD mode, not calendar day mode. To run the model in

GDD mode, observations of phenological growth stages in calendar days must be converted to GDDs with the daily temperature file used to calibrate the model.

6.1.2.2 Model inputs

6.1.2.2.1 Soil data

The minimum soil input parameters required by AquaCrop are shown in Table 6-6 (cf. Section 6.2.2.3.3). For the A- and B-horizons, the Terrain Unit Database recently developed by Schulze and Schütte (2023) contains soil depths and soil water retention parameters for up to five terrain units within each of the 7 082 land types across South Africa (Figure 6-2). This database of soil parameters for 27 473 terrain unit polygons was used to provide area-weighted values for each altitude zone (AZ) located in South Africa (described later in Section 6.2.2.4.1). These improved soil parameters for South Africa were then merged with previous values derived for Lesotho and Eswatini using other soil databases, since land type data does not exist for these two neighbouring countries (Clulow et al., 2023; cf. Chapter 2). The saturated hydraulic conductivity of the topsoil was calculated from equations provided by Saxton and Rawls (2006). The above-mentioned soil parameters for all 5 838 AZs were packaged together to develop the Altitude Zones Soil Database.

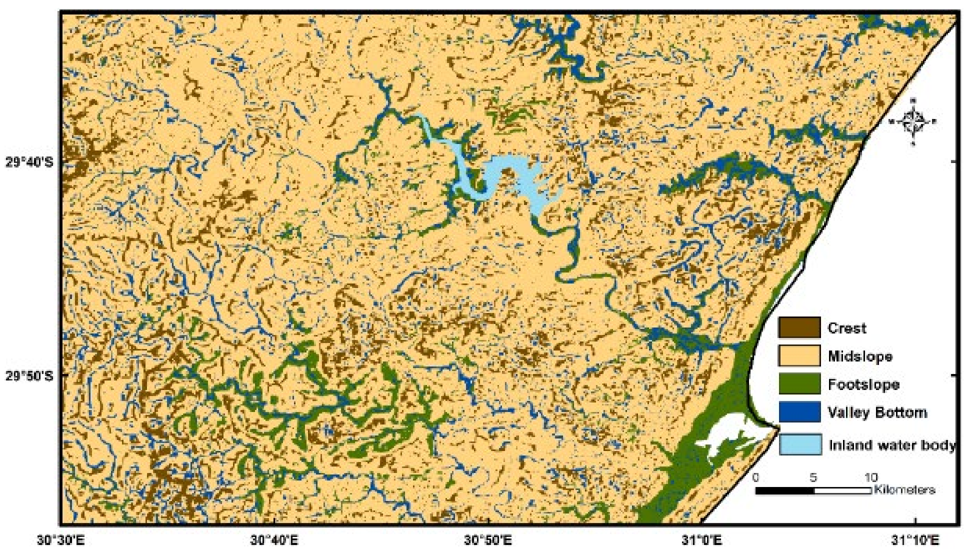

Figure 6-2 Terrain unit polygons shown for the Durban metropolitan area and surrounding region

6.1.2.2.2 Climate data

Rainfall: A representative driver rainfall station from the Lynch (2004) dataset was selected for each quaternary catchment (Schulze et al., 2011). In total, 1 240 driver stations were selected for the 1 946 quaternaries. For each selected station, daily rainfall from January 1950 to December 1999 was extracted from the rainfall database developed by Lynch (2004). Kunz et al. (2020) identified 13 extreme daily rainfall events exceeding 400 mm, with the worst case being 900.5 mm. Each extreme event was compared to corresponding data from ten neighbouring stations available in the Lynch (2004) rainfall database and four extreme rainfalls were downward adjusted. In addition, the driver rainfall station for 11 quaternary catchments was changed to improve the representation of the rainfall for those catchments.

For each AZ, monthly adjustment factors were then derived by comparing the driver station's median monthly rainfall to that derived for each zone using spatial estimates of median monthly rainfall developed by Lynch (2004). The monthly adjustment factors were then applied to daily rainfall values from the selected driver station to improve the representativeness of the rainfall for each zone. Hence, each AZ has a unique time series of daily rainfall data from 1950 to 1999.

Temperature: Similarly, a driver temperature station from the Schulze and Maharaj (2004) dataset was selected for each quaternary (Kunz et al., 2020). For each of the 543 selected driver stations, daily temperature from January 1950 to December 2000 was extracted from the temperature database developed by Schule and Maharaj (2004). A total of 114 temperature stations have the same SAWS ID as the driver rain gauge, meaning that both rainfall and temperature were measured at the same weather station. A lapse rate adjustment was applied to account for the altitude difference between the selected temperature station and the average altitude across each AZ. Hence, a unique time series of daily temperature data from 1950 to 1999 was developed for each AZ.

Reference evapotranspiration: Daily ET_O values for each AZ were then calculated from the lapse-rate adjusted temperatures using the FAO56 version of the Penman-Monteith equation (Allen et al., 1998). Owing to the lack of available wind speed data across South Africa, a daily default value of 2 m s^{-1} was used for each AZ, as suggested by Allen et al. (1998).

The above-mentioned daily rainfall, temperature and ET_O datasets were combined to produce a daily climate file with data from 1950 to 1999 deemed representative of each AZ. All 5 838 climate files were packaged together to develop the Altitude Zones Climate Database (Kunz et al., 2020). The climate files are stored in ACRU composite format (Smithers and Schulze, 1995) for running the ACRU model (cf. Section 6.2.2.1), which have also been converted to the format required by AquaCrop (Kunz et al., 2024).

6.2.2.3 Model parameters

A full calibration of AquaCrop for a new crop (known as model parameterisation) involves the determination of locally derived values for most of the model's input parameters. Model parameterisation for a new crop requires well designed experiments where crop growth parameters (e.g. leaf area index, photosynthetically active radiation, canopy cover development, plant height, leaf number, root development etc.) are frequently measured during the growing season, for both non-stressed and water-stressed growing conditions.

A combination of controlled (pot), field and/or rain shelter experiments are usually conducted to obtain crop growth, yield and water use data. Typically, measurements from non-stressed (i.e. irrigated) treatments are used to calibrate most of the crop parameters, whereas parameters related to water stress effects are adjusted using data collected from the water deficit treatments. Rain shelter experiments are ideal for controlling crop water availability and for including additional water treatments (e.g. moderate deficit and severe deficit irrigation). In addition, experiments are usually conducted over consecutive seasons to provide data for both model calibration and validation (i.e. testing). Other measurements of soil water content and crop evapotranspiration can also be used to test the crop model's ability to predict these variables. Kephe et al. (2021) stated that if primary datasets are unavailable for model calibration, secondary datasets can be sourced from both grey and peer-reviewed literature. Models can also be "loosely" calibrated by adjusting parameters within a reasonable range, or by using parameters available for a similar crop.

The model parameterisation process typically requires a dedicated full-time PhD student to (i) correctly design the experiment, (ii) conduct the required measurements over two seasons, (iii) analyse the measurements, (iv) finalise the full calibration (using data from the first season), and finally (v) perform the validation (with data from the second season). Owing to the complexity of this approach, it was not adopted in this project and existing crop parameters for *C. sativa* were used instead.

6.2.2.3.1 Existing crop parameters

A simpler method for determining crop parameter values utilises a technique known as ideotyping, which approximates parameter values based on already calibrated crops. Default parameter values for a new crop are first obtained from another similar crop, then adjusted using secondary datasets obtained from field work conducted by others, which have been published or are freely available. For example, Averink (2015) developed AquaCrop parameters for hemp, with default values for most parameters obtained from barley. Similarly, Wimalasiri et al. (2021a) used sugarcane parameters to calibrate AquaCrop for hemp, since both crops have similar growth habitats. These two studies are presented next in more detail.

<u>Case study 1: Averink (2015)</u>: The parameter values developed for hemp by Averink (2015) are shown in Appendix E (Table E-1 of this report). The line numbers shown in the table correspond to an AquaCrop v6 crop parameter file. Averink (2015) simulated both fibre and seed yield, as well as crop water use to estimate the water footprint of hemp. An initial canopy cover (CC_O) of 3.75% was computed by AquaCrop using a very high plant density of 2.5 million seeds ha^{-1}. Maximum canopy cover (CC_X) was calculated as 95% (line no. 50 in Table E-1) using a maximum leaf area of 4.25 m^2 m^{-2} obtained from the literature. Beer-Lambert equations developed for cotton (García-Vila et al., 2009) and maize (Hsiao et al., 2009) were used, with the light extinction coefficient (k) set to 0.60. However, Averink (2015) incorrectly calculated CC_X, with correct values being 91% and 93% using the two equations. Furthermore, k is close to 1 for hemp as reported by De Meijer et al. (1995) and Tang et al. (2018).

The time to reach CC_X was 80 days was used to estimate the canopy growth coefficient (CGC = 7.9% day^{-1}; line no. 46). The time to reach senescence (100 days; line no. 54) and physiological maturity (120 days; line no. 55) was used to calculate the canopy decline coefficient (CDC = 7.7% day^{-1}; line no. 51), which is the same value for barley (Raes et al., 2018). Since the parameters used by Averink (2015; Table E-1) were not validated, which the author recommended for future work, they were not used in this project.

<u>Case study 2: Wimalasiri et al. (2021a)</u>: Wimalasiri et al. (2021a) sourced crop parameters related to phenology, canopy development and harvest index from the available literature. Biomass and yield (fibre and seed) datasets were also sourced from the literature and used for model calibration and validation. These datasets were developed by Tang et al. (2017) to assess light and nitrogen distribution profiles of hemp canopies in response to nitrogen deficiency. A medium maturing, monoecious cultivar from France (Futura 75) was planted in April 2014 (calibration) and April 2015 (validation) at Piacenza, Italy (45.0°N; 9.8°E; 60 m a.s.l.). The experiment was planted at a density of 120 plants m^{-2}, which was mostly rainfed but received supplemental irrigation.

For model calibration, the following parameters were modified: (i) base and upper temperature, (ii) minimum and maximum effective rooting depth, (iii) rate of canopy development (CC_O, CGC, CC_X and CDC), (iv) phenological growth stages, (v) WP*, (vi) HI_O, and the 3) onset, rate and duration of harvest index build up. Simulations of seed yield and biomass (seed and fibre) were compared against observations using the root mean square error (RMSE) statistic. It is important that AquaCrop simulates canopy cover development well, since it is used to calculate transpiration, which is then used to estimate biomass production and finally yield. However, the simulation of canopy cover development (in %) was not given by Wimalasiri et al. (2021a). The outcome of the calibration and validation procedure, which is shown in Table 6-1, was deemed acceptable due to the low RMSE values (< 0.2 t ha^{-1}). However, calibration and validation statistics for hemp fibre yield were not given. Based on this, the crop parameters developed by Wimalasiri et al. (2021a) were used in this project.

Table 6-1 Calibration and validation results for hemp seed and fibre (biomass) yield (Wimalasiri et al., 2021a)

Type	**Variable**	**Observed (t ha^{-1})**	**Simulated (t ha^{-1})**	**RMSE (t ha^{-1})**
Calibration	Seed yield	1.8	2.1	0.1
	Biomass (seed) yield	7.1	8.3	**1.2**
	Biomass (fibre) yield	11.4	13.3	0.2
Validation	Seed yield	2.1	2.2	0.1
	Biomass (seed) yield	9.8	9.5	0.3
	Biomass (fibre) yield	12.5	12.3	0.2

Case study 3: Wimalasiri et al. (2021b): Wimalasiri et al. (2021b) also published parameter value for hemp fibre and seed yield. Table 6-2 highlights differences in parameter values between the 19th of June and 3rd of September publications. Some parameter values for sugarcane were not modified for hemp, e.g. water stress during flowering (0.90; line no. 19) and time to maximum rooting depth (60 days; line no. 53). One can assume that the latter values (i.e. Wimalasiri et al., 2021b) are more correct, except for the harvest index value of 100% being an obvious error. An additional parameter value at line no. 60 was published by Wimalasiri et al. (2021b). Wimalasiri et al. (2021b) simulated hemp fibre and seed yield for six locations in Malaysia using climate input from 2010 to 2019, resulting in average potential seed and fibre yields of 1.61 ± 0.25 and 2.78 ± 0.39 t ha^{-1}, respectively. They calculated minimum economically feasible yields of 3.62 t ha^{-1} (fibre) and 1.38 t ha^{-1} (seed).

Table 6-2 *Comparison of crop parameters published for hemp by Wimalasiri et al. (2021a; 2021b)*

No.	**Crop parameter**	**Fibre**		**Seed**	
		2021a	**2021b**	**2021a**	**2021b**
46	Canopy growth coefficient (CGC in % day^{-1})	11.917	11.917	24.917	11.150
58	Crop determinacy unlinked with flowering				
56	Calendar days from sowing to flowering	72	**89**	74	**89**
57	Length of the flowering stage (days)	17	**12**	17	17

59	Buildup of harvest index (%)	15	**10**	15	15
60	Length of harvest index buildup period (days)	90	90		
61	Normalised water productivity (WP* in g m^{-2})	18	**15**	25	**15**
64	Reference harvest index (HI_O in %)	**100**	**10**	23	18

Crop parameter files: Of the 60 parameters required by AquaCrop, 34 are considered important as shown in Table E-1. Of these, Wimalasiri et al. (2021a; 2021b) published 23 values in June 2021 (cf. Table 1, p. 4) and September 2021 (cf. Table 2, p. 4). Owing to differences in these published parameter values, the main author was contacted to obtain copies of the actual crop parameters files (Wimalasiri, 2023; pers. comm.). Values highlighted in bold in Table E-1 differ to those published by Wimalasiri et al. (2021b), which highlights the importance of obtaining the original crop parameter file from the authors and not relying on published values. For this project, the assumption is made that parameter values listed in the crop files obtained from Dr Wimalasiri are correct and that the discrepancies in published values are due to changes made by the authors to the crop parameter files after the paper publication dates.

6.2.2.3.2 Model calibration

Steduto et al. (2012) recommended the following cultivar-specific parameters should be "fine-tuned" to account for local cultivars/landraces and climatic conditions:

a) planting date and planting density (line no. 45 in Table E-1);
b) maximum canopy cover (line no. 50);
c) maximum rooting depth (line no. 38);
d) time required to reach maximum rooting depth (line no. 53);
e) reference harvest index (line no. 64); and
f) length of each phenological growth stages (line no. 52 to 57), in particular the crop cycle length (i.e. time to physiological maturity; line no. 55).

Since the field and pot experiments undertaken in KwaZulu-Natal and the Eastern Cape focused on bud yield, measurements and observations could not be used to fine-tune (or validate) the model parameters developed by Wimalasiri et al. (2021b). As described next, only the planting date, plant density and maximum rooting depth parameters were altered to represent fibre and seed production in southern Africa.

Planting date: Initial model runs for seed and fibre (biomass) yield were conducted for altitude zone 4697 (Pietermaritzburg, KwaZulu-Natal), where the planting month was varied from October to January. The results showed the maximum seed and fibre (biomass) yield was obtained for the December planting (Table 6-3). Hence, the planting month was set to December for both fibre (biomass) and seed production, which represents the first planting month for 42.7% of all AZs (Figure 6-3).

Table 6-3 AquaCrop simulations of seed and fibre (biomass) yield for altitude zone 4697 in KwaZulu-Natal

Planting month	Yield (dry t ha^{-1})	
	Seed	**Biomass**
Oct	1.174	8.016
Nov	1.186	7.937
Dec	**1.194**	**8.078**
Jan	1.122	7.459

The planting day was to the 1st of the month so that plant evapotranspiration (ET) is accumulated over the entire month, which prevents under-estimation of the initial crop coefficient (Kunz et al., 2020; 2024). For example, if the planting date is set to the 15th, the initial crop coefficient would be estimated from only half of the ET data. For floral production at Kenlei Farms, seedlings (Charlotte's Angel) were planted in the south field, whereas clones (Cherry Blossom) were planted in the east and north fields. Planting took place from the 21-28 November 2022.

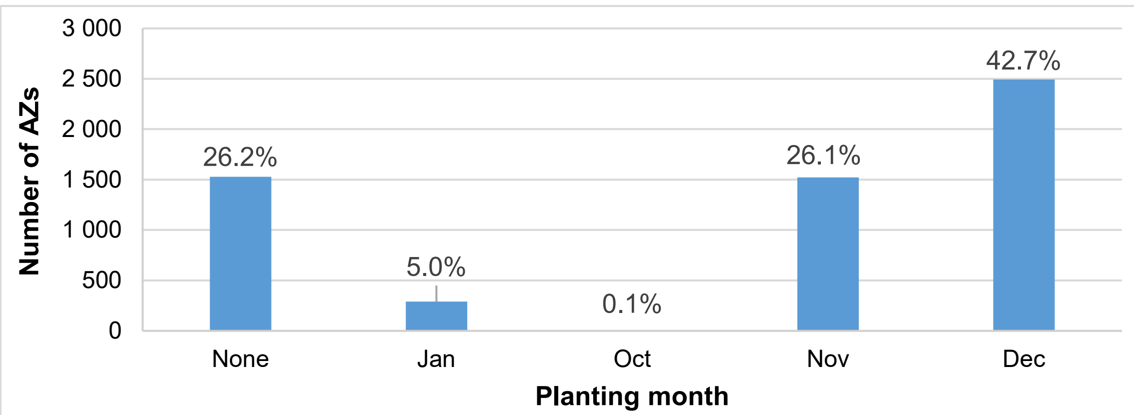

Figure 6-3 Histogram of the average planting month determined from 50 years of climate record for each of the 5 838 altitude zones (Kunz et al., 2020)

<u>Plant density</u>: The plant density depends on the end use of cannabis. For floral production, much lower plant densities are recommended but values vary widely in the literature (Table 6-4). In the south field at Kenlei Farms, feminised seedlings were planted at a density of 2 000 plants ha^{-1}, which represents a row and plant spacing of 2.5 m and 2.0 m respectively. The plant population was thinned to 1 035 plants ha^{-1} after the removal of male plants. As noted in Section 6.1.1, such low plant densities are highly unlikely to negatively impact downstream water availability.

As shown in Table 6-4, Amaducci et al. (2015) recommended sowing at a higher density (90-200 plants m^{-2}) for fibre production compared to a lower density (30-75 plants m^{-2}) for seed production. Slender stems are desirable for fibre production to encourage long fibres, which require less energy for mechanical processing. Thus, plant density for biomass production is about double that for seed production. However, plant densities exceeding 150 plants m^{-2} are not recommended because they increase the risk of lodging due to the fine stems (Tang et al., 2017). Struik et al. (2000) stated that crops with an initial plant density of 30-90 plants m^{-2} generally maintained this density throughout the growing season, whereas crops planted at 180-270 plants m^{-2} showed evidence of self-thinning. Plant densities below 100 plants ha^{-1} reduce weed growth (Sebastian et al., 2023). Planting at higher densities reduces airflow amongst the plants, which increases the risk of disease. The density values used by Wimalasiri et al. (2021a; 2021b) for fibre and seed production are considered too low (cf. Table E-1). Based on the above, plant densities of 150 and 75 plants m^{-2} were used in this project for fibre and seed production respectively. This avoids self-thinning and lodging, which AquaCrop cannot simulate. For simplicity and to allow comparison of simulations from one AZ to another, the same values were used for each altitude zone across the country.

Table 6-4 Planting density for three different products of hemp cultivation

Plants ha^{-1}			Source
Fibre	**Seed**	**Floral**	
90-200	30-75	10-15	Amaducci et al. (2015)
40-60			Jiang et al. (2018; China)
	33-37		Deng et al. (2019)
30	14		Wimalasiri et al. (2022; Malaysia)
		0.59-0.98	García-Tejero et al. (2020; Spain)
		0.30-1.20	da Silva Benevenute et al. (2021)
		0.36-0.72	Linder et al. (2022)
		0.16-0.20	Denton (2024)

<u>Maximum canopy cover</u>: Maximum canopy cover (CC_X) values given in the crop parameter files of 90 and 85% for fibre and seed production were not adjusted. However, these values were 5% lower than those published by Wimalasiri (2021a; 2021b). The values are much higher than CC_X estimated for bud production at Kenlei Farms in the 2022/23 season, as described next.

From measurements of leaf area index (LAI), CC_X can be estimated using the Beer-Lambert equation, assuming the extinction coefficient (k) is known for the crop. This crop-specific value should be 1) estimated from measurements of photosynthetically active radiation (PAR) over the growing season, or 2) obtained from the literature. Averink (2015) used a value of 0.60 for k, whereas De Meijer et al. (1995) and Tang et al. (2018) reported a value of 0.96. Using a maximum LAI of 0.877 m^2 m^{-2} measured at 67 DAP (Denton, 2024), CC_X was calculated as 0.51 (51%) using the equation provided by Hsiao et al. (2009), with k set to 0.96. A similar value of 0.52 (52%) was calculated for the north field from a maximum LAI of 0.892 m^2 m^{-2}.

<u>Effective rooting depth</u>: Destructive sampling is required to determine the minimum (Zr_{min}) and maximum (Zr_{max}) effective rooting depths. The time taken to reach Zr_{max} is used by the model to compute the root expansion rate (in cm d^{-1}). Since these observations could not be made at Kenlei Farms, values obtained by Wimalasiri et al. (2021b) were used. However, Zr_{max} was decreased from 2 m to 1 m since soil depths derived from the land types are limited to a standard auger length (1.2 m maximum).

<u>Reference harvest index</u>: This parameter (HI_O) represents the portion of crop biomass that produces economic yield. AquaCrop adjusts HI_O depending on the level of water and/or

temperature stress experienced during the growing season. HI_O is calculated using measurements of final biomass and yield at time of harvest from non-stressed field experiments, where water stress is alleviated through application of supplemental irrigation. Wimalasiri et al. (2021a) published values of 100% and 23% for fibre and seed production respectively, where the former value is obviously an error. These values were reduced to 10% and 18% by Wimalasiri et al. (2021b), which match the values in the actual crop parameter files obtained from the main author. They are within the range of 2.5% to 22.5% reported in the literature (Tang et al., 2016), and thus were not altered. However, HI_O for bud production is likely to be different. Although a bud yield of 3 500 g per plant was measured at Kenlei Farms (Denton, 2024), above-ground biomass was not measured, which means HI_O could not be calculated. Similarly, the pot and field experiments did not produce seed as the buds were harvested before pollination took place. For indoor plants, yield is typically measured in g per m^2, with plants commonly producing 400-500 g m^{-2}.

Phenological growth stages: The time taken to reach each phenological stage is recorded in days until ≥ 50% of the plant population exhibited diagnostic signs of that particular growth stage. For example, duration of flowering is recorded as time taken from flowering until 50% of the plant population exhibited anthesis. Physiological maturity occurs when dry matter accumulation (biomass and yield) ceases. The values extracted from the crop parameter file for fibre and seed production are shown in Table 6-5, which for seed production, are slightly different to those published by Wimalasiri et al. (2021b). The times to reach senescence and physiological maturity are used by the model to calculate the canopy decline coefficient (CDC), which explains why CDC for fibre production is slightly lower than the value for seed production (cf. Table E-1). Similarly, the canopy growth coefficient (CGC) is calculated by the model using the initial canopy cover (CC_O) and the time taken to reach CC_X.

Table 6-5 Time to reach each phenological growth stage in calendar days for fibre and seed production (after Wimalasiri et al., 2021b)

No.	Crop parameter	Fibre	Seed
	Phenological growth stages (in GDDs) from sowing to:		
69	- emergence	10	10
70	- maximum rooting depth	60	60
71	- start senescence	105	**100**
72	- maturity (length of crop cycle)	140	**135**
73	- flowering	89	89
74	Length of the flowering stage	12	**17**
77	Building-up of Harvest Index during yield formation	90	90

From Table 6-5, the time from sowing to the start of flowering is 89 days. In comparison, the season length at Kenlei Farms ranged from 134 (seedlings; south field) to 163 days (clones; north field), i.e. from transplanting (not sowing) to full flowering. This may indicate the climate was not warm enough to maximise plant growth.

Ideally, crop phenology should be converted from calendar days to growing degree-days (GDD; i.e. thermal time). This is done in AquaCrop with the daily temperature record used for model calibration. To calculate GDDs, AquaCrop utilises a method described by McMaster and Wilhelm (1997), with the exception that no adjustment of minimum temperature is made when it drops below the base temperature. This is believed to better represent the damaging or inhibitory effects of cold temperatures on plant processes. In AquaCrop, this method of calculating GDDs is known as "METHOD 3". However, the project was unsuccessful in obtaining the daily temperature file from Wimalasiri (2023) for Piacenza (Italy) from 2014 (calibration) to 2015 (validation). Hence, the model was run in calendar day mode, not GDD mode, as was done by Wimalasiri et al. (2022).

<u>Other parameters</u>: In addition to the parameters highlighted by Steduto et al. (2012), other relatively important values to obtain via measurements (or from the literature) are as follows:

a) Base and upper temperature (°C) affecting crop growth (line no. 08 and 09 in Table E-1): According to Wimalasiri et al. (2021b), values of 1.5 and 40°C were obtained from Amaducci et al. (2012). Wimalasiri et al. (2021b) also provided absolute temperatures for marginal hemp growth of 6-32°C, including optimal temperatures of 15-28°C.

b) Seedling leaf area at 90% emergence (line no. 43 and 44): this measurement, together with plant density, is used by the model to compute initial canopy cover (CC_O) as described by Raes et al. (2009);

c) Basal crop coefficient (K_{CB} on line no. 35): the value was set to 0.96, compared to 1.10 for sugarcane. According to Pereira et al. (2021), K_{CB} values for hemp, jute or sisal have not been published in papers. Hence, the origin of this value is unknown. From measurements of ET in the south field at Kenlei Farms, monthly averaged K_C peaked at 0.71 in February and March, and thus K_{CB} is 0.71, given that K_{CB} is 0.05 less than K_C (Pereira et al., 2021).

None of the above parameter values were adjusted in this project.

6.2.2.3.3 Model validation

AquaCrop is typically validated against independent measurements of leaf area index (i.e. canopy cover development), final biomass accumulation and seed/grain yield, i.e. measurements not used in the calibration process. In addition, measurements of crop evapotranspiration and soil water content can also be used to validate adjusted model parameters. In order to validate the model, it is important to ensure the following:

- representative daily rainfall and temperature data are collected at or nearby the simulation field;
- the evaporating power of the atmosphere (ET_O) is correctly determined;
- field management practices that a) affect soil surface runoff, b) reduce soil water evaporation (i.e. mulches), and c) crop development and production (e.g. soil fertility) are specified correctly in the model; and
- the physical soil characteristics of the various soil horizons are well defined (FAO, 2015).

The soil parameters required by AquaCrop are listed in Table 6-6, which provides default values for each soil textural class (Raes et al., 2022). Soil parameters are required for each soil horizon, including its depth. Ideally, these values should be determined from undisturbed soil cores taken from the experimental field. Alternatively, the SPAW model (Saxton and Rawls, 2006) can be used to estimate the parameters from measurements of clay, silt and sand percentages for each soil horizon.

Table 6-6 Default soil parameters required as input for AquaCrop (Raes et al., 2022)

Soil texture	**θ_{SAT}**	**θ_{FC}**	**θ_{PWP}**	**K_{SAT}**
	(%)			**(mm d^{-1})**
Sand	36	13	6	3 000
Loamy sand	38	16	8	2 200
Sandy loam	41	22	10	1 200
Silt loam	46	33	13	575
Loam	46	31	15	500
Silt	43	33	9	500
Sandy clay loam	47	32	20	225
Clay loam	50	39	23	125
Silty clay loam	52	44	23	150
Silty clay	54	50	32	100
Sandy clay	50	39	27	35
Clay	55	54	39	35

Fibre and seed production were simulated using AquaCrop, not bud yield. Since the field and pot experiments undertaken in KwaZulu-Natal and the Eastern Cape focused on bud yield, the measured data could not be used to validate the model parameters developed by Wimalasiri et al. (2021b).

6.2.2.4 National model runs

As part of numerous WRC-funded projects, considerable effort has been spent on developing an automated methodology to run AquaCrop for each of the 5 838 AZs across the country. These zones are described next, as well the development of the automaton process.

6.2.2.4.1 Altitude zones

South Africa was delineated into a set of nested primary, secondary, tertiary and quaternary catchment boundaries by the Department of Water and Sanitation in 2018. There are 22 primary catchments that have been delineated into 1 946 quaternary catchments as shown in Figure 6-4. Owing to the relatively large variation in altitude across each quaternary, especially in mountainous regions, each catchment was further subdivided into three regions of similar altitude called altitude zones (Schulze and Horan, 2011). This delineation was based on natural breaks in altitude using the Jenk's optimisation method available in the ArcGIS software suite (ESRI, California, USA). Each of the 5 838 (i.e. 1 946 * 3) AZs represent regions of similar topography within each quaternary. They can be considered as relatively homogeneous response zones, with minimal variation in climate and soils across each zonal polygon. Therefore, these AZs are particularly useful for agricultural-related assessments involving crop simulation models to determine, amongst others, crop water use and yield. Hence, the AZ boundaries were selected in this project as the spatial mapping unit.

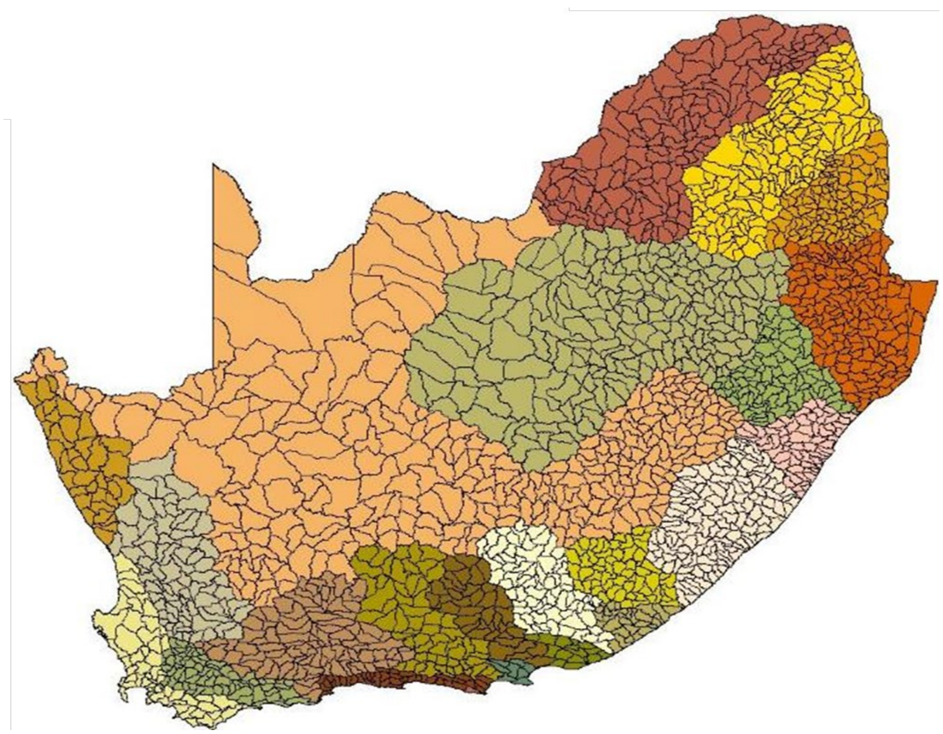

Figure 6-4 Quaternary catchments boundaries within each of the 22 primary drainage basins

6.2.2.4.2 Automation process

For WRC Project K5/1874, Kunz et al. (2015) initially developed a methodology to run AquaCrop for all 5 838 AZs, each with 50 years of daily climate input. The automated process also generates long-term monthly and seasonal statistics for each AquaCrop output variable. These statistics were used to develop the maps shown in Section 6.1.3. Since this task is computationally expensive, considerable effort was spent in automating the national model runs. Kunz et al. (2020) made additional improvements as part of WRC Project K5/2491, reducing the time required to perform these large model runs by ~80%, i.e. from 62 to 12 hours. Thereafter, Kunz and Mabhaudhi (2023; WRC Project K5/2717) also made other improvements to reduce the time required to complete a national run. More recently, Kunz et al. (2024) made the most significant improvements to the automation process, further reducing the national run time to 5-6 hours. Further improvements are expected as part on an ongoing WRC Project (C2023/2024-01254) that ends in March 2027. Approximately 10 000 lines of code written in Bash (Unix), Fortran and Python have been developed and maintained to facilitate the national-scale model runs.

6.1.3 Results and Discussion

To re-cap, AquaCrop was run for all 5 838 AZs using input soil and climate data described in Section 6.1.2.2. Two crop parameter files developed by Wimalasiri et al. (2021b) for hemp were obtained from the main author in 2023, with slight adjustments made to three crop parameters to better represent local growing conditions. Two national model runs were undertaken to simulate both fibre and seed yield under rainfed conditions. The fibre parameter file was used to simulate fibre yield (cf. Section 6.3.1.1) and biomass production (cf. Section 6.3.1.3), while the seed parameter file was used for seed yield (cf. Section 6.3.1.1), crop water productivity (cf. Section 6.3.1.2) and crop cycle length (cf. Section 6.3.1.4). AquaCrop was run in calendar day mode, not the preferred growing degree-day mode, which affects the accuracy of the simulations (cf. Section 6.3.1.5). The importance of planting date on model simulations is discussed in Section 6.3.1.6.

6.3.1.1 Fibre and seed yield

Hemp is considered a dual-purpose crop that produces both fibre and seed, which is profitable in many European countries (Tang et al., 2016). Hemp is a bast fibre crop since the fibre is contained in the outer layers of the stem, i.e. in the bark (Leoni et al., 2022). Although fibre was the main product of hemp cultivation in Europe over the past decade, this has recently shifted to seed and floral bud cultivation (Leoni et al., 2022). For this reason, both fibre and seed yield were simulated across the southern African region (South Africa, Lesotho and Eswatini). All AZs were simulated, since it is not known which zones are considered suitable for hemp production. It is important to note that AquaCrop simulates dry (not fresh) crop yield.

Simulated fibre yield is lower than seed yield across all AZs (Figure 6-5). On average, fibre yield is 0.31 t ha^{-1} less than seed yield, with the range being 0.03 to 0.49 t ha^{-1}. The standard deviation of the difference is 0.11 t ha^{-1}, resulting in a high inter-seasonal variation of 34.9%. Figure 6-5 shows spatial differences between hemp seed and fibre yield in t ha^{-1} for each AZ. Differences are smallest (< 0.20 t ha^{-1}) in the drier western parts of the country, where seed yield is lowest (< 0.5 t ha^{-1}; cf. Figure 6-8). Hence, zones with low seed yield also have low fibre yield, thus resulting in a small difference between the two yields. In contrast, zones with a high seed yield exhibit a lower fibre yield.

Lower fibre yield compared to seed yield is expected since yield in AquaCrop is the product of accumulated above-ground biomass production and the harvest index or HI (cf. Section 6.1.2.1). Since the crop cycle length for fibre yield was five days longer than for seed yield (Table E-1; cf. line no. 55), biomass (fibre) production for fibre was greater biomass (seed) production by 0.85 dry t ha^{-1} (on average). However, as shown in Table E-1 (line no. 64), HI is 10% for fibre compared to 18% for seed, thus resulting in lower fibre and higher seed yields.

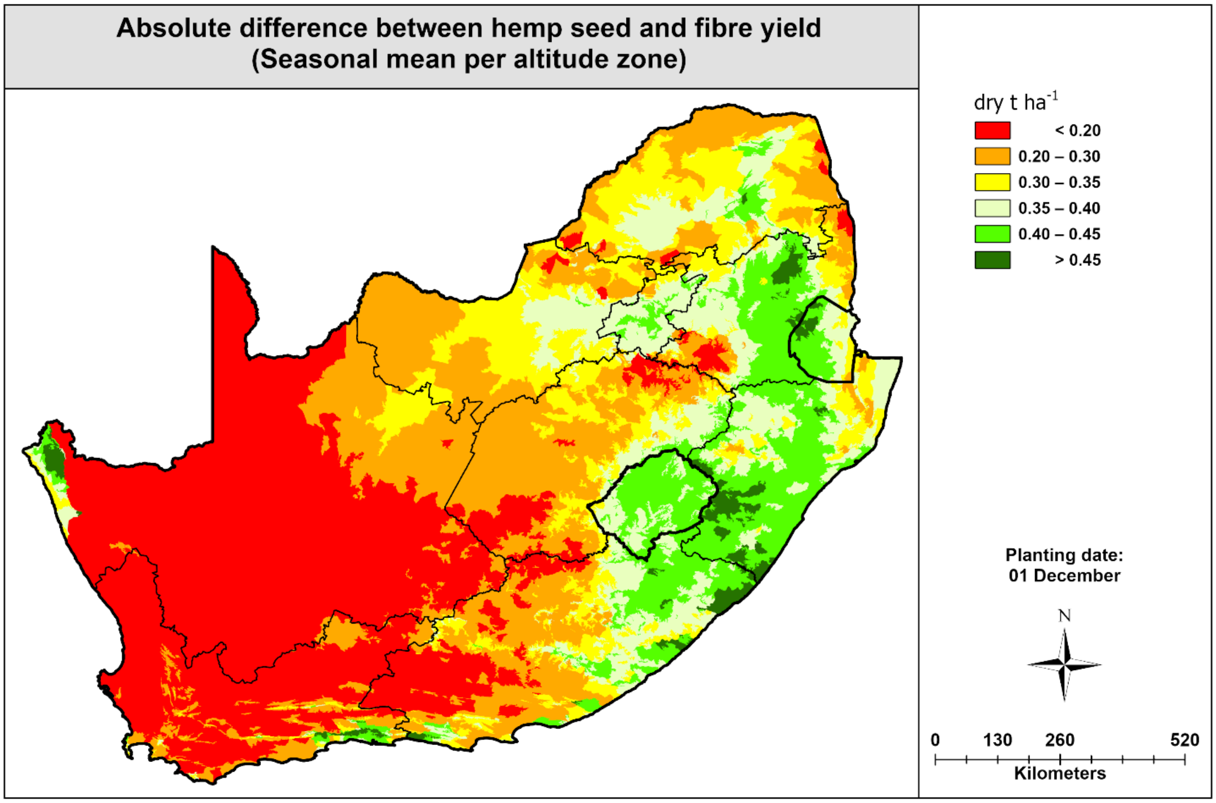

Figure 6-5 Difference between hemp seed and fibre yield per altitude zone

AZs with a small difference (i.e. < 0.3 t ha^{-1}) are mostly considered unsuitable for rainfed hemp production (coloured red and orange in Figure 6-5), which corresponds to 40.9% of all AZs (Figure 6-6). About 28% of the zones exhibit a difference between seed and fibre yield that exceeds 0.40 t ha^{-1}, which correspond to highly suitable production areas (coloured light and dark green in Figure 6-5).

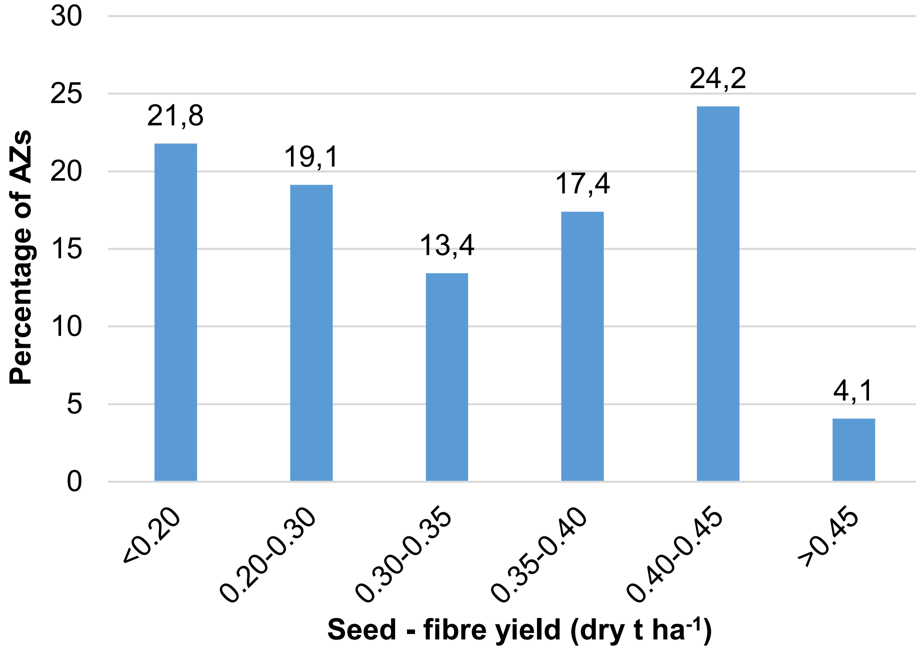

Figure 6-6 Histogram of the difference between hemp seed and fibre yield per altitude zone

The difference was also expressed as a percentage relative to hemp seed yield. The percentage difference steadily decreases from west to east across the country (Figure 6-7). Not all AZs in southern Africa are suited to the rainfed production of hemp, as expected. Zones with a higher percentage difference (coloured red and orange in Figure 6-7) are not suited to hemp production, whereas zones with a smaller percentage difference (coloured light and dark green in Figure 6-7) are better suited to hemp cultivation. The dark green zones occur in the higher rainfall areas along the eastern seaboard, especially in areas well suited to sugarcane and commercial forestry. The average decrease from seed to fibre yield is 36.5% (range 15.9-46.6%), with a standard deviation and CV of 4.3 and 11.9%, respectively.

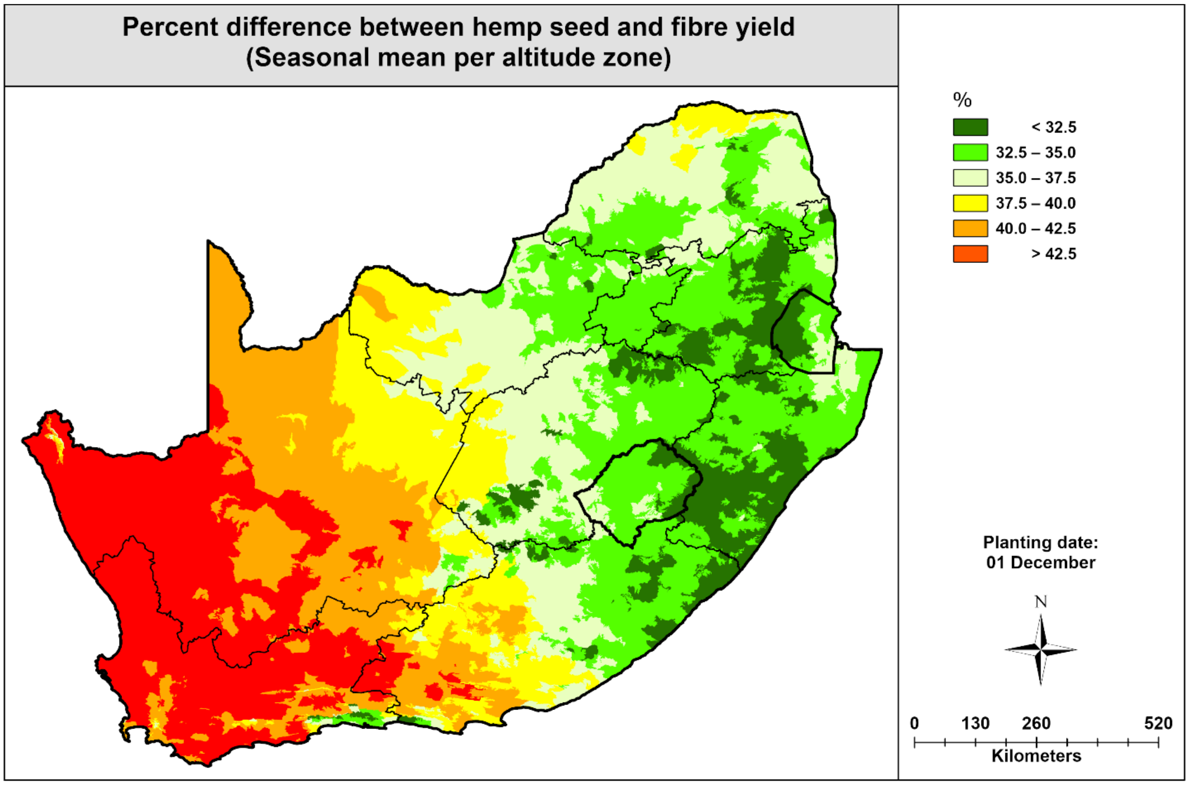

Figure 6-7 Difference between hemp seed and fibre yield per altitude zone, expressed as a percentage

Figure 6-8 shows the average hemp seed yield in dry t ha^{-1} derived from 49 seasonal simulations from 1950/51 to 1998/99 for each of the 5 838 AZs. Simulated seed yield ranges from 0.14 and 1.48 dry t ha^{-1}, with a spatial average of 0.89 t ha^{-1} across the southern African region. The standard deviation is 0.37 t ha^{-1}, which results in a high coefficient of variation (CV) of 41.9%, due mostly to the large variation in spatial rainfall. As expected, the map shows the highest seed yields are attainable along the eastern seaboard of the country, due to the favourable magnitude and monthly distribution of summer rainfall. Thus, KwaZulu-Natal, Mpumalanga and the north-eastern region of the Eastern Cape are most suited to hemp production. Large parts of the country's interior region, especially towards the western areas, are probably too dry for economically viable production of hemp under rainfed conditions.

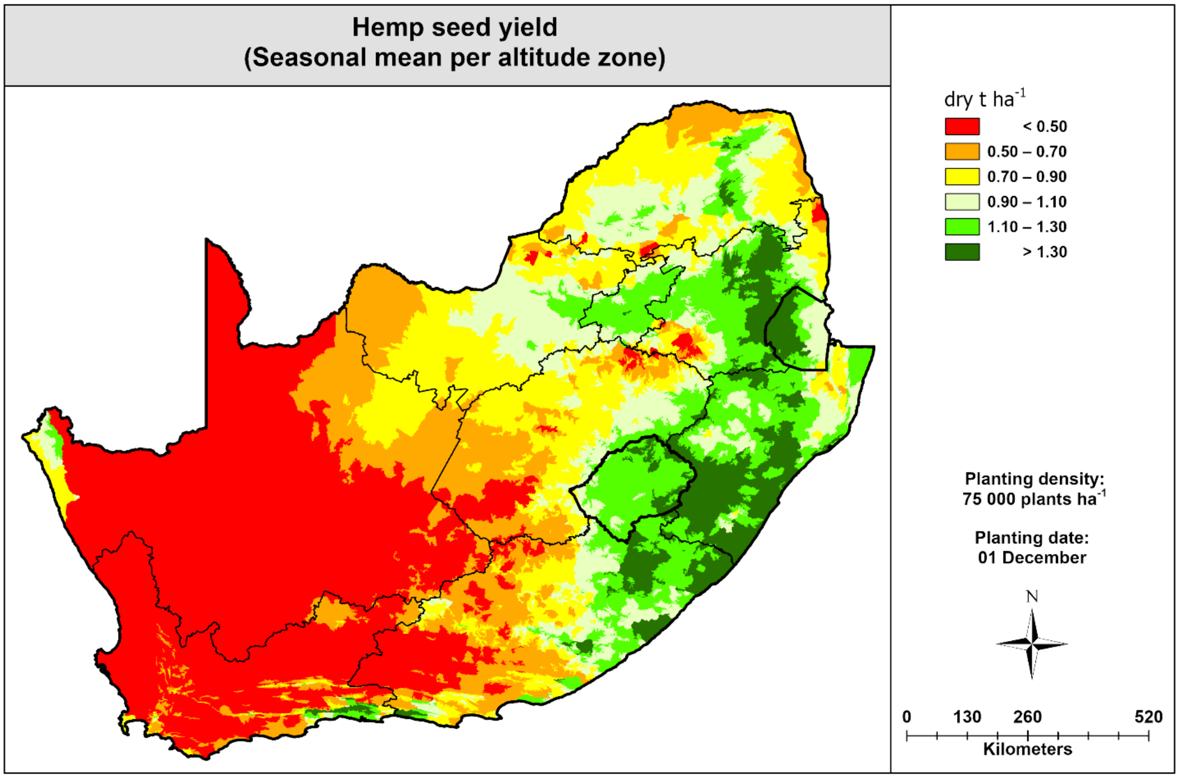

Figure 6-8 AquaCrop simulations of hemp seed yield (average of 49 seasons) per altitude zone

Altitude zones where the average yield exceeds 1.30 dry t ha^{-1} may be considered highly suitable for hemp production, which represents 16.3% of all zones (Figure 6-9). Moderately and marginally suitable zones correspond to yield ranges of 1.10-1.30 and 0.70-1.10 t ha^{-1}, respectively. Hence, 21% and 28% of the AZs are considered moderately and marginally suited to hemp cultivation. Zones with an average yield below 0.70 t ha^{-1} (34% of the total) could be considered unsuitable for hemp cultivation.

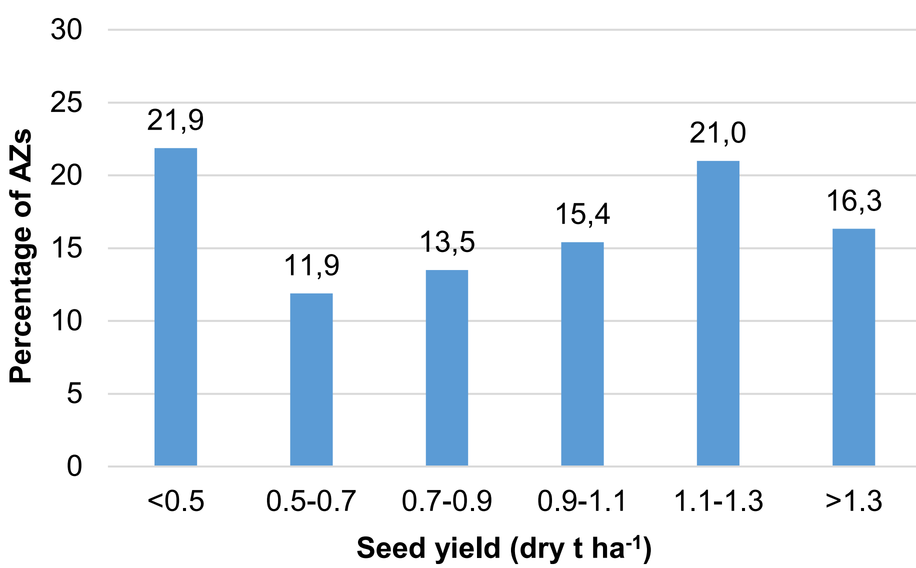

Figure 6-9 Histogram of average hemp seed yield per altitude zone

Wimalasiri et al. (2022) simulated hemp fibre and seed yield at six locations in Malaysia. Soil data from the Soilgrids database (v2.0; soilgrids.org) was used as input for AquaCrop, together with historical climate data spanning 10 years (2010 to 2019). According to Steduto et al. (2012), at least 20 years of daily climate data should be used to simulate the long-term attainable yield at a particular location. However, 30 years of data is considered the de facto standard for calculating statistics. Despite this, the mean and dispersion in simulated yield was calculated by Wimalasiri et al. (2022) as shown in Table 6-7, which show yields for Malaysia are higher than those simulated for southern Africa. This is expected due to Malaysia's tropical climate, where mean annual precipitation (MAP) ranges from 1 807 to 2 940 mm (Wong et al., 2016). In Table 6-7, the standard deviation and range typically decreases with increasing yield, i.e. lower yield variability in highly productive areas.

Table 6-7 Summary statistics of hemp fibre and seed yield for six locations in Malaysia (Wimalasiri et al., 2022)

Location	Fibre yield (t ha^{-1})			Seed yield (t ha^{-1})		
	Mean	**Std. dev**	**Range**	**Mean**	**Std. dev**	**Range**
Temerloh	2.14	1.16	0.01-3.24	1.21	0.74	0.00 - 1.90
Kuala Terengannu	2.49	0.59	1.10-3.09	1.40	0.43	0.39 - 1.82
Senai	2.81	0.99	0.00-3.23	1.65	0.58	0.00 - 1.90
Petaling Jaya	3.00	0.28	2.24-3.19	1.76	0.19	1.24 - 1.88
Alor Setar	3.10	0.17	2.68-3.25	1.81	0.11	1.53 - 1.91
Cameron highlands	3.13	0.10	2.95-3.24	1.84	0.05	1.74 - 1.90

Tang et al. (2016) assessed 14 hemp cultivars grown in four European countries, which showed bast fibre yields were 208-333% higher than seed yields (1.3-7.4 vs 0.3-2.4 t ha^{-1}), with bast fibre content ranging from 21-43%. However, Wimalasiri et al. (2022) simulated fibre yields that were only 70-78% (average 73%) higher than seed yields (cf. Table 6-7). In contrast, fibre yields simulated by AquaCrop for southern Africa were 15.9-46.4% lower than seed yields (0.08-1.02 vs 0.14-1.48 t ha^{-1}).

Wimalasiri et al. (2022) used ordinary kriging to interpolate yield across Malaysia. The bright yellow spot situated near the centroid of the Malaysian Peninsular in Figure 6-10 shows the sensitivity of kriging to the point estimate for Temerloh. The authors also produced a land suitability map (not shown here) using a traditional approach involving simple overlays of seasonal climate (rainfall and temperature), edaphic (soil texture, depth and pH) and topographic (elevation) data. Soil pH was assigned the highest weighting (60%), whilst texture and depth were assigned equal weightings (20%). However, the highly suitable areas did not correlate with the higher yielding areas to the north of Temerloh, as shown in blue in Figure 6-10.

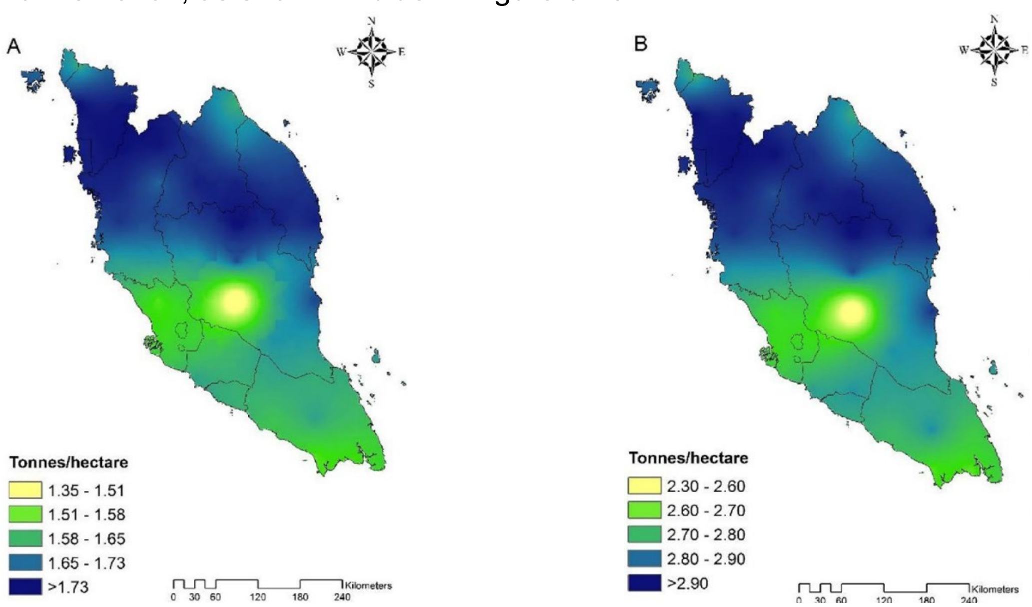

Figure 6-10 Interpolated seed (A) and fibre (B) yield of hemp across Malaysia based on ordinary kriging (Wimalasiri et al., 2022)

6.3.1.2 Crop water productivity (seed)

Crop water productivity (CWP) is a useful metric that represents the ratio of crop yield per unit of crop water use (i.e. evapotranspiration accumulated over the growing season). The metric is therefore sensitive to yield (e.g. biomass, fibre, seed, and floral buds), and thus areas where yield is high typically exhibit high CWP. As shown in Figure 6-11, hemp is most water use efficient when producing seed along the coastal (and adjacent interior) areas of southern KwaZulu-Natal, and the Eastern and Western Cape.

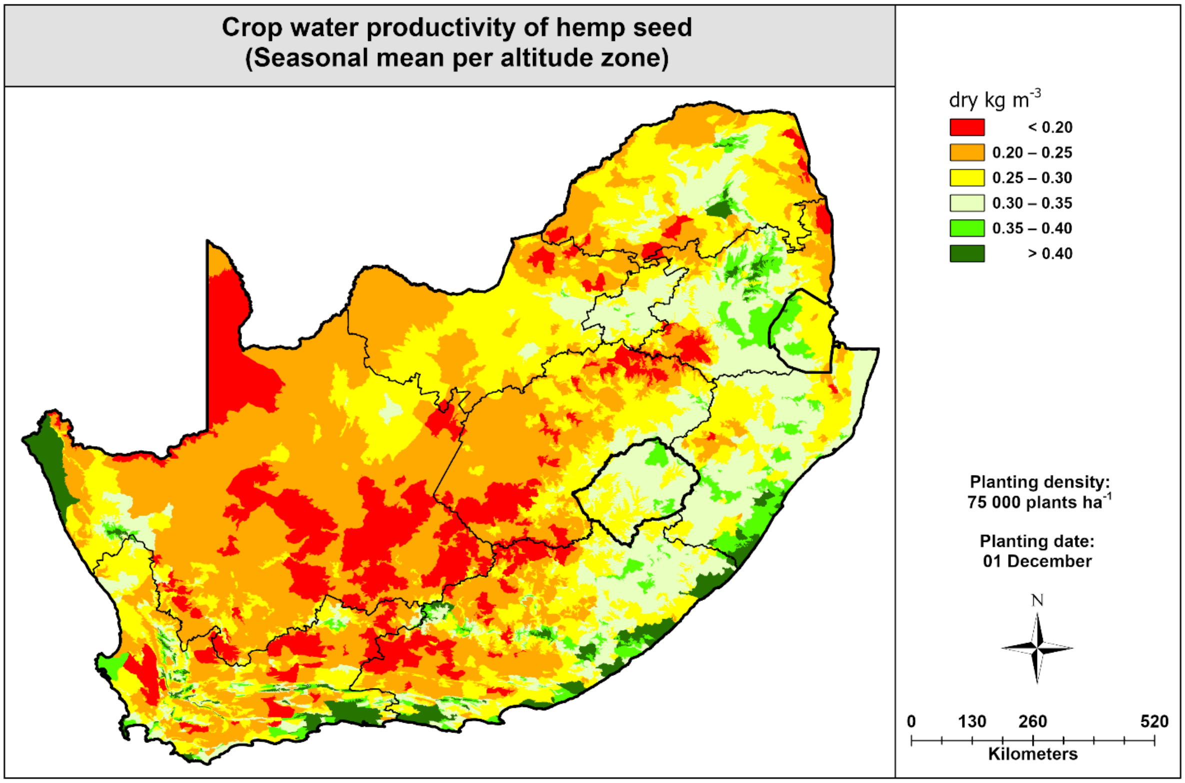

Figure 6-11 Simulated crop water productivity for seed production per altitude zone

The minimum and maximum simulated CWP values for hemp seed (CWP_{SEED}) are 0.05 and 1.32 kg m^{-3}, respectively. The average is 0.30 kg m^{-3}, with a standard deviation of 0.09 kg m^{-3} and CV of 30.3%. As shown in Figure 6-12, production of hemp seed should be promoted in 7.1% of the zones with highest CWP_{SEED}. For just over half of all AZs (57.2%), CWP_{SEED} ranges from 0.25 to 0.35 dry kg m^{-3}.

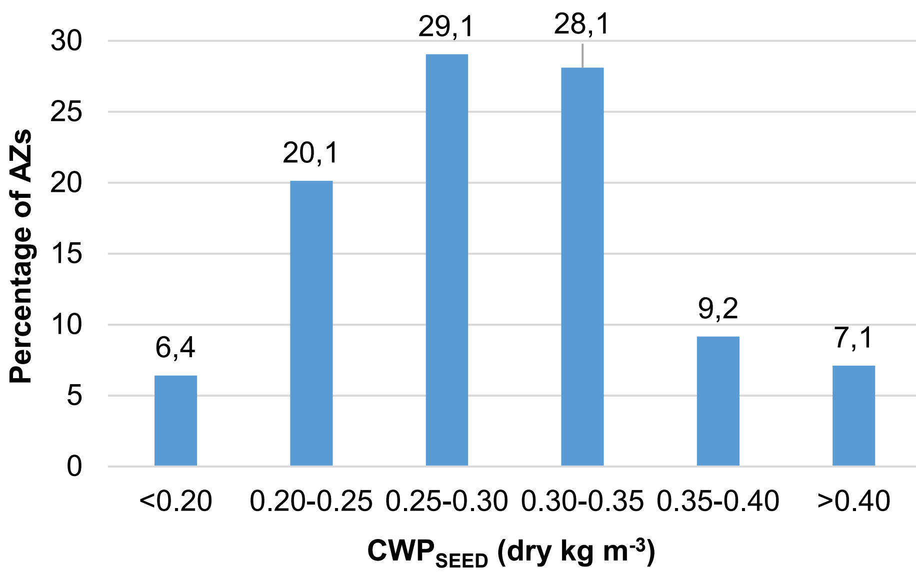

Figure 6-12 Histogram of average crop water productivity for seed production per altitude zone

CWP_{SEED} values simulated by Wimalasiri et al. (2022) for six locations in Malaysia are shown in Table 6-8, which are fairly similar to values for southern Africa. However, the highest average value of 0.50 dry kg m^{-3} for Malaysia is much lower than 1.32 dry kg m^{-3} for southern Africa. Amaducci et al. (2015) reported that little information exists on hemp's CWP. Hence, the CWP simulations for hemp seed production in (i) southern Africa (this report), and (ii) Malaysia (by Wimalasiri et al., 2022) represent a valuable contribution that addresses this knowledge gap.

Table 6-8 Summary statistics of crop water productivity of hemp seed yield for six locations in Malasyia (after Wimalasiri et al., 2022)

Location	CWP_{SEED} (dry kg m^{-3})		
	Mean	**Std. dev**	**Range**
Temerloh	0.27	0.16	0.00-0.39
Kuala Terengannu	0.35	0.10	0.11-0.46
Senai	0.38	0.14	0.00-0.46
Petaling Jaya	0.40	0.04	0.29-0.44
Alor Setar	0.44	0.02	0.40-0.47
Cameron highlands	0.50	0.02	0.48-0.54

When compared to other emerging crops such as sweet potato (Figure 6-13) and taro, CWP_{SEED} values for hemp are much lower. The white areas in Figure 6-13 are considered too cold for viable production of sweet potato. Kunz et al. (2024) ran AquaCrop in growing degree-day mode, which provides more realistic simulations of CWP when compared to running the model in calendar day mode, as was done in this project and by Wimalasiri et al. (2022). This is very important to understand, and thus is further explained in Section 6.3.1.5.

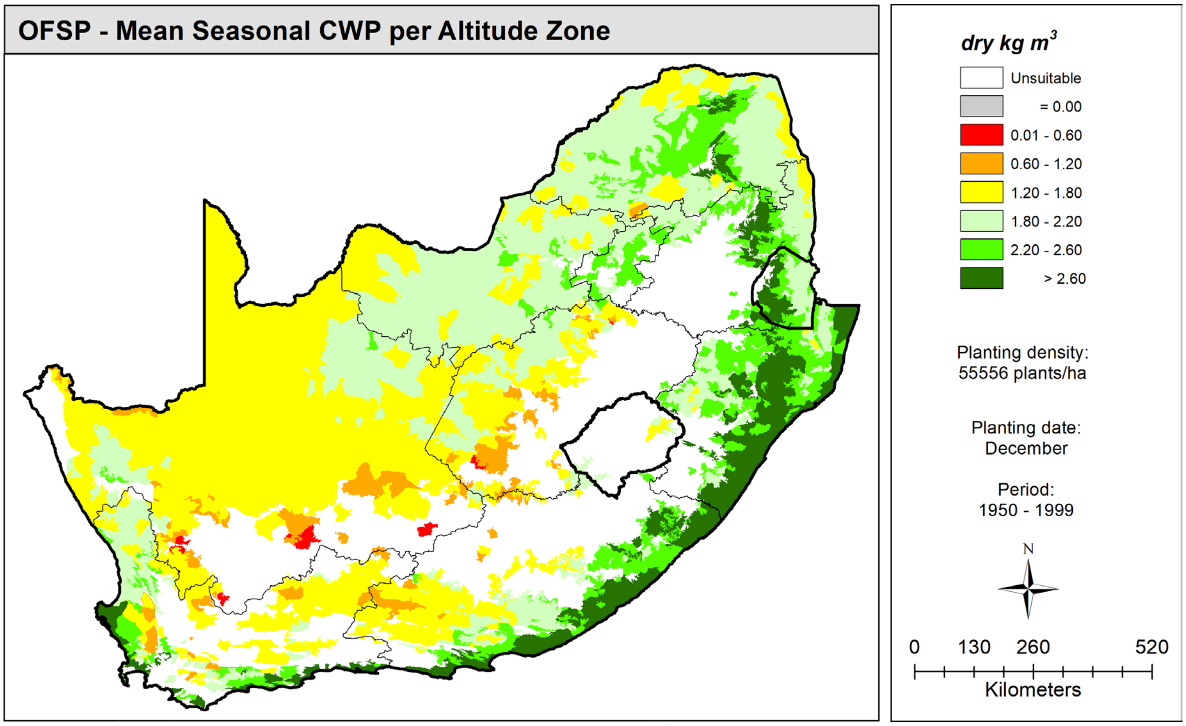

Figure 6-13 Simulated crop water productivity per altitude zone for orange flesh sweet potato (OFSP) planted in December at a density of 55 556 plants ha^{-1} (Kunz et al., 2024)

It is important to note that CWP_{FIBRE} will be different to CWP_{SEED}. As reported in Section 6.3.1.1, fibre yields across all AZs were on average 36.5% lower than seed yields, which will result in lower CWP_{FIBRE}. In contrast, Wimalasiri et al. (2022) simulated higher fibre yields (by 73% on average) when compared to seed yields, i.e. CWP_{FIBRE} > CWP_{SEED}. Similarly, CWP_{FLORAL} will be different to CWP_{SEED}. For example, Denton (2024) calculated a water productivity of 0.96 fresh kg m^{-3} for bud yield in the south field at Kenlei Farms, based on a bud yield of 3 623 fresh kg ha^{-1} and total ET over the growing season of 377 mm.

When compared to seed, fibre and floral bud yield, hemp produces more biomass yield (i.e. production in dry kg ha^{-1}), and thus $CWP_{BIOMASS}$ > CWP_{SEED}. The higher biomass values are shown in Section 6.3.1.3. Cosentino et al. (2013) reported $CWP_{BIOMASS}$ (cultivar Futura 75) values up to 3.45 kg m^{-3}. Hence, hemp is about 3.5 times more water use efficient at producing biomass than cotton, since $CWP_{BIOMASS}$ for cotton is ~1 kg m^{-3} (Himanshu et al., 2023).

Long-term water stress increases leaf senescence and reduces canopy photosynthetic nitrogen-use efficiency (Tang et al., 2018). However, hemp can withstand moderate water deficit, and although yields of biomass, seed, fibre and floral buds are reduced, CWP is likely to increase when the crop is water stressed. For example, Cosentino et al. (2013) reported that when water stressed, $CWP_{BIOMASS}$ harvested before flowering increased from 1.91 to 2.48 kg m^{-3}, whereas $CWP_{BIOMASS}$ harvested after flowering increased from 2.73 to 3.45 kg m^{-3}. Hence, biomass should be harvested after flowering to allow more time for biomass accumulation.

6.3.1.3 Biomass production (fibre)

Industrial hemp has also emerged as a commercial crop for high biomass production and carbon sequestration, with various end-use products, e.g. bioenergy and paper. Hence, the decision was made to map biomass production, which Wimalasiri et al. (2022) did not consider for Malaysia. As noted in Section 6.3.1.1, biomass (fibre) production is higher than that for seed production by 0.85 dry t ha^{-1} on average, except in 199 zones. Biomass (seed) was marginally higher than biomass (fibre) by up to 0.19 t ha^{-1} in only 15 of the 199 zones. Hence, the average production of hemp biomass (fibre) in dry t ha^{-1} was mapped as shown in Figure 6-14. AZs along the eastern seaboard simulated the highest biomass production, which results in higher fibre (and seed) yields (cf. Figure 6-8).

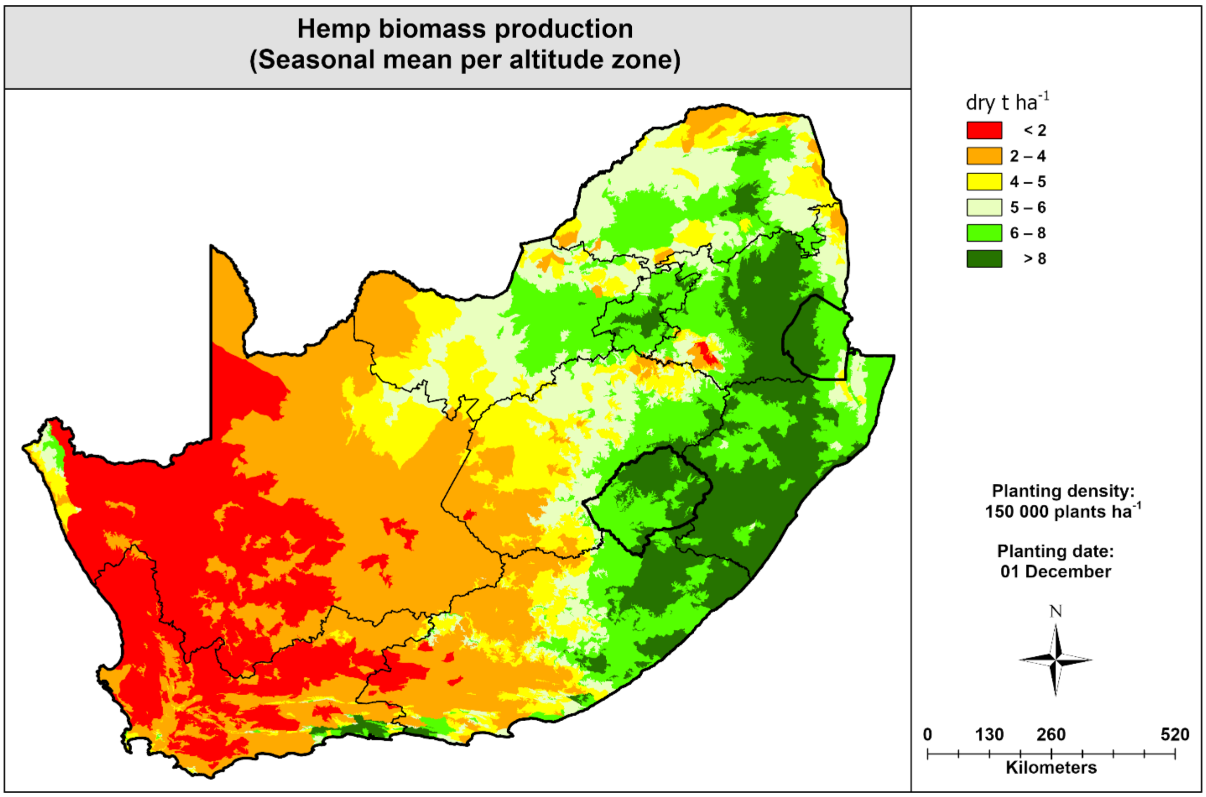

Figure 6-14 AquaCrop simulations of hemp biomass production (average of 49 seasons) per altitude zone

Biomass (fibre) production averages 5.80 t ha^{-1}, with a standard deviation and CV of 2.66 t ha^{-1} and 45.9%, respectively. As shown in Figure 6-15, biomass production exceeds 8 t ha^{-1} in ~27% of the AZs, peaking at 10.21 t ha^{-1}. In the drier western parts of the country (or ~31% of the AZs) that are not suited to hemp, biomass production ranges from 0.81 to 4.00 t ha^{-1}. About 43% of the AZs are considered moderately suitable for biomass production, where values range from 4-8 t ha^{-1}.

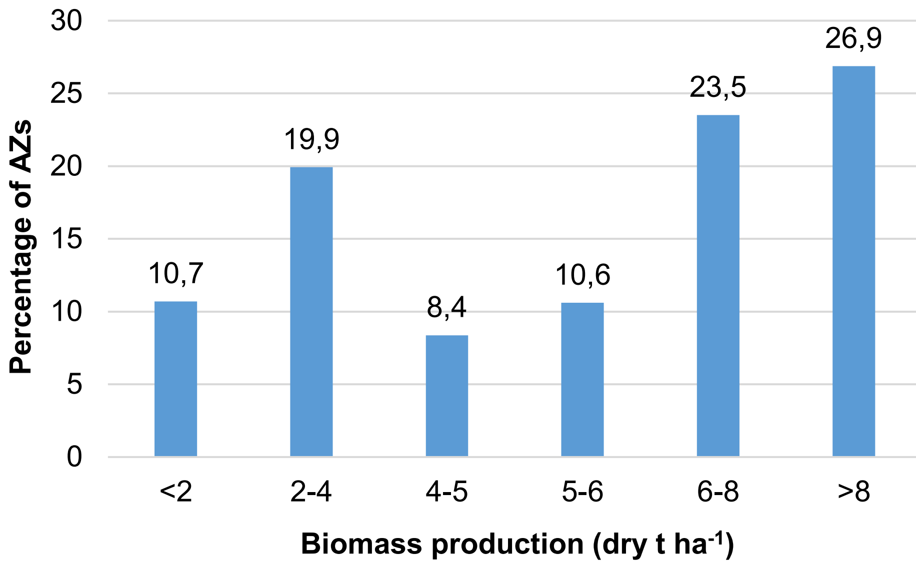

Figure 6-15 Histogram of average hemp biomass yield per altitude zone

Struik et al. (2000) reported that hemp can produce up to 25 dry t ha^{-1} of above-ground biomass. The range of biomass production reported by Tang et al (2016) was 3.7-22.7 t ha^{-1} across four European countries (Latvia, Czech Republic, France, Italy). Hence, when compared to these four countries, maximum biomass potential in southern Africa is 45% of Europe's maximum.

6.3.1.4 Crop cycle length (seed)

The calibrated crop cycle length (from sowing to physiological maturity) was 135 days for hemp seed production, i.e. 5 days less than that for fibre production. Values simulated by AquaCrop are always less than 135 days because the crop cycle length excludes time from sowing to germination, which takes 10 days (cf. Table E-1). The average length is 113 days, with a very small standard deviation (7 days) and CV (6.2%). The crop cycle length is relatively similar for all AZs because AquaCrop was run in calendar day mode and not the preferred growing degree-day mode, which is further discussed in Section 6.3.1.5. The length ranges from 118-119 days for about one-third of all AZs, which are mostly located in the higher rainfall areas (Figure 6-17), where MAP exceeds 800 mm.

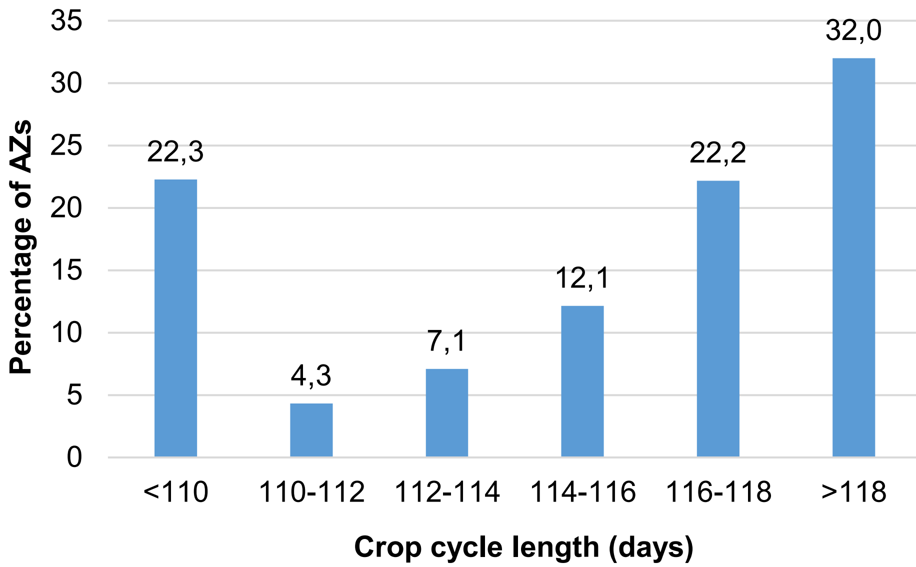

Figure 6-16 Histogram of average season length for seed production per altitude zone

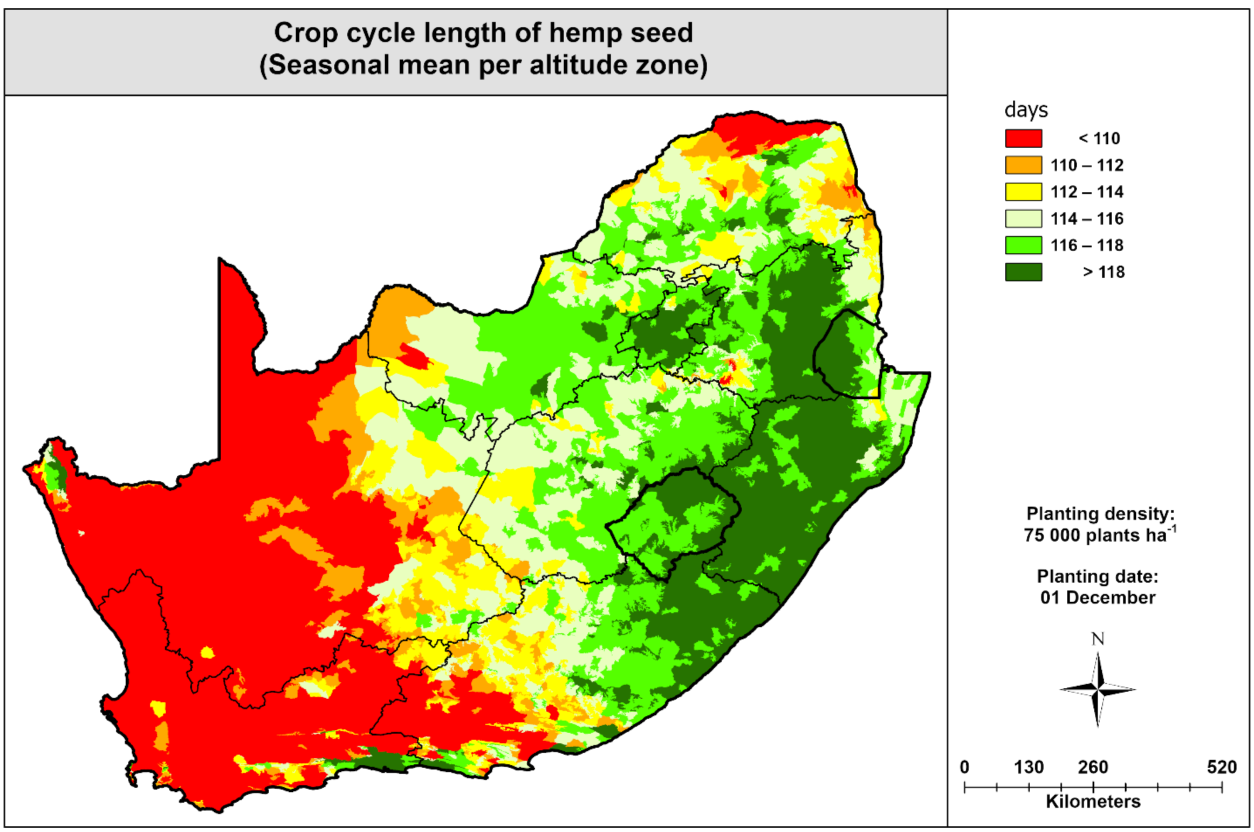

Figure 6-17 Average length of the growing season for hemp seed production as simulated by AquaCrop

The distribution of crop cycle length is skewed by values below 110 days, which occurs in ~22% of the altitude zones (Figure 6-16). The shortest crop cycle length in five AZs is 85 days, due to dry conditions that results in water stress that typically ends crop growth. As shown in Figure 6-17, these dry altitude zones are located in the western parts of the country, where MAP is below ~300 mm, and thus not suited to rainfed crop production.

Hemp's growth cycle consists of four growth stages: (i) germination and emergence, (ii) vegetative growth, (iii) flowering and seed formation, and (iv) senescence. The vegetative phase can be further subdivided into a juvenile, photo-sensitive and flower development phase (Amaducci et al., 2015). In general, sown seeds typically germinate in the first 14 days. Seedlings take a further 21 days to grow, followed by up to 56 days (8 weeks) of vegetative growth. During pre-flowering (7-14 days), male or dual-sex plants produce pollen, which can pollinate nearby female plants, leading to seed production. Therefore, the time from sowing to pre-flowering stage is ~91 days, which concurs with the calibrated value of 89 days (cf. Table E-1; line no. 56).

It is important to note that the length of each phenological growth stage varies widely depending on, inter alia, cultivar (e.g. dioecious vs monoecious plant) and location (e.g. daylength). For example, Tang et al. (2016) reported 50% emergence between 6-12 days, whereas the duration of the vegetative phase (from emergence until flowering) ranged from 56-121 days. Full flowering and seed development can take 56 days (Amaducci et al., 2008a) to 84 days (Tang et al., 2016) to complete, i.e. the duration of flowering varied widely in the literature. However, little information exists in the literature on the start and duration of senescence. Overall, the total season length (from sowing to physiological maturity can range from 147-175 days (5-6 months), which is longer than the calibrated value of 135-140 days determined by Wimalasiri et al. (2021b). Hemp produces fibre during the vegetative stage, whereas cotton must be grown to the flowering state, i.e. hemp has a shorter growth cycle for fibre production when compared to cotton (Gill et al., 2023).

6.3.1.5 Calendar days vs growing degree-days

When AquaCrop is run in calendar day mode, hemp's season length is a maximum of 135-140 days after planting. The crop cycle length excludes time to emergence, and thus is 10 days shorter than the season length. However, water stress can further shorten the crop cycle length, particularly in dry and hot (high ET_O) climates (cf. Figure 6-17).

Soybean has a similar season length of 135 days, which is equivalent to 2 025 growing degree-days (GDDs) to reach physiological maturity. When AquaCrop is run in GDD mode, the crop cycle typically ends when sufficient GDDs have been accumulated (not at 135 days after planting). This is shown in Figure 6-18 for soybean planted in December, which clearly shows hot altitude zones (formerly known as quinary sub-catchments) where the crop reaches maturity before 135 days. Similarly, in cold zones (i.e. mountainous areas), the crop takes much longer to accumulate the required number of GDDs, and thus the crop cycle length extends well beyond 135 days. In Figure 6-18, AZs in white exhibit a crop cycle length exceeding 365 days, which is economically unviable, especially for frost-sensitive crops. Hence the model is not run for such zones, which are typically located in Lesotho and along the Drakensberg Mountain range. In comparison, Figure 6-17 shows simulated crop cycle lengths for hemp that range from 116-119 days for AZs in Lesotho, which is unlikely due to cold temperatures. It is clear that running AquaCrop in GDD mode results in a much larger and more realistic variation in crop cycle lengths.

Kunz et al. (2020; 2024) ran AquaCrop in GDD mode, which also provides more realistic simulations of yield and CWP when compared to running the model in calendar day mode, as was done in this project and by Wimalasiri et al. (2022). In calendar day mode, AquaCrop tends to overestimate biomass production, fibre/seed yield, water use and CWP since transpiration and the harvest index are not affected by water and temperature stress. As explained in Section 6.1.2.1, biomass is calculated from accumulated transpiration and yield is estimated from biomass via the harvest index.

From Table 6-7 (cf. Section 6.3.1.1), Wimalasiri et al. (2022) simulated zero yields (i.e. total crop failures for one (or more) seasons for Temerloh and Senai. Similarly, zero yields were only simulated in 22 AZs (range of 1-7 seasons, with 3 seasons on average). This is far less than expected and occurred because AquaCrop was run in calendar day, and thus water and temperature stress is not considered.

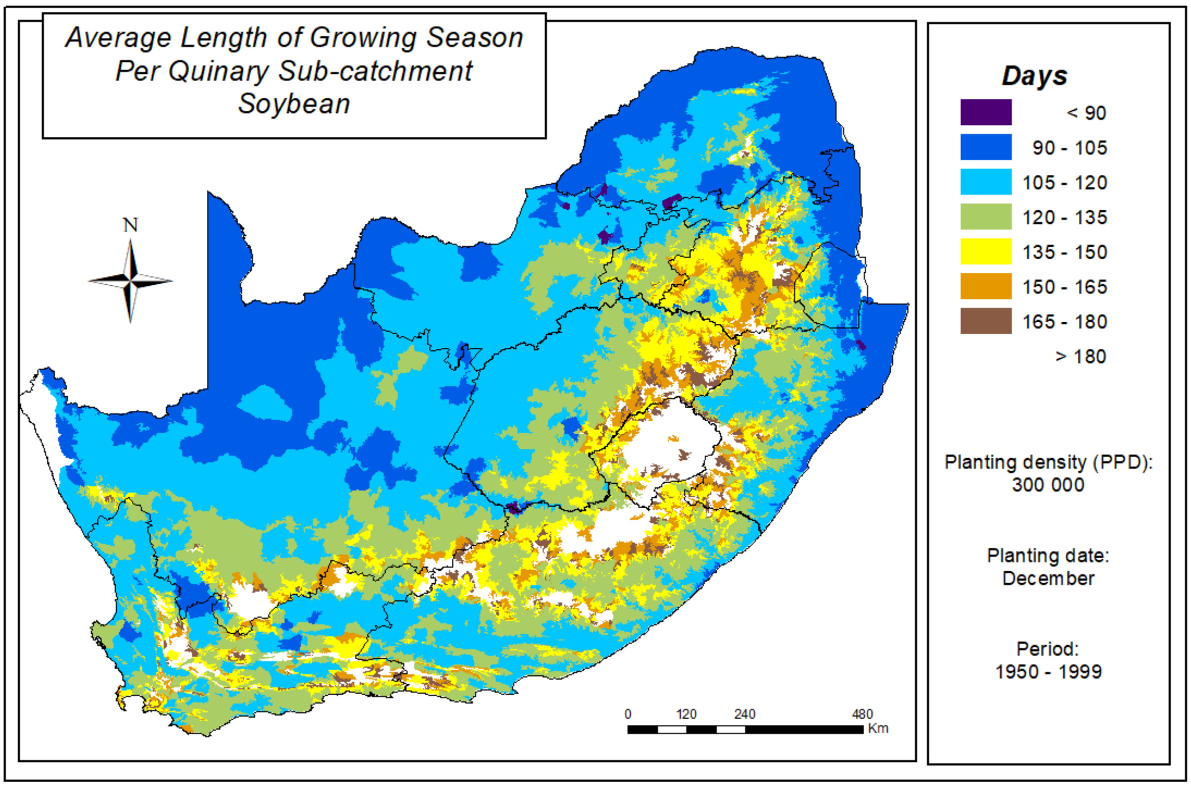

Figure 6-18 Average crop cycle length for soybean planted in December as simulated by AquaCrop (Kunz et al., 2020)

6.3.1.6 Planting date

In South Africa, hemp can be grown outdoors from September to the end of February. A January planting is useful for restricting plant height to 250 cm. Hemp is a short-day plant that is sensitive to the photoperiod, which means flowering is induced after several consecutive days of shorter daylength. Hence, hemp growth is vegetative when daylengths are long (12-14 hours). Flowering can be induced when daylengths are shorter than 12 hours (i.e. nights are longer), which occurs from March to September in the southern hemisphere (Table 6-9). However, a long dark period may cause early flowering and reduced yield (Sebastian et al., 2023). In addition, artificial shading (i.e. using shade cloth) can also help to induce flowering (DeDecker, 2019).

Since hemp phenology is dependent on daylength, it is possible to maximise seed yield in a given environment by choosing an appropriate cultivar and/or planting date. For example, monoecious varieties are better suited to seed production (Amaducci et al., 2015). For seed production, the goal is to maximise flowering, which is induced by shorter daylengths. Hence, a December planting ensures that flowering, which starts approximately three months after planting (cf. Section 6.3.1.4), coincides with 11-12 hours of daylight (i.e. shorter days) in March and April (Table 6-9).

For bioethanol, bioenergy or biogas production, the goal is to maximise biomass (i.e. stem) growth. Maximising vegetative growth can be achieved by planting a late flowering cultivar (Amaducci et al., 2015), which typically have low seed yields (Tang et al., 2016). For non-limiting conditions, stem growth is proportional to the duration of the vegetative growth phase. Maximising vegetative growth can be achieved by delaying the onset of flowering (Amaducci et al., 2015) by extending the photoperiod (longer exposure to daylight). Therefore, an October planting would (i) prolong the vegetative phase (allowing more time for stem growth), and (ii) ensure that the flowering period in December/January coincides with longer daylengths (12-14 hours) (Table 6-9).

Table 6-9 Maximum hours of daylight from October to April for the northern (Limpopo), central (Free State) and southern (Cape Town) regions of South Africa

Latitude (°S)	Province	Oct	Nov	Dec	Jan	Feb	March	April
-22	Limpopo	12.5	13.1	13.3	13.2	12.7	12.1	11.5
-23	(Musina)	12.6	13.1	13.4	13.3	12.8	12.1	11.5
-28	Free State	12.7	13.4	13.8	13.6	13.0	12.2	11.3
-29	(Bloemfontein)	12.7	13.5	13.9	13.7	13.0	12.2	11.3
-34	Western Cape	12.9	13.8	14.3	14.0	13.3	12.2	11.1
-35	(Cape Town)	12.9	13.9	14.4	14.1	13.3	12.2	11.1

For textile and paper production, the goal is to maximise the quantity and quality of fibre production. The male plants of dioecious hemp varieties exhibit superior fibre quality. Hence, farmers in Europe and China typically harvest male plants for production of fine textiles, while female plants are used for manufacturing coarse fabrics (Amaducci et al., 2015). High bast content is desirable due to its high-cellulose and long fibre lengths, which is generally considered of higher value than the plant’s woody core (Tang et al., 2016). In the future, model runs for multiple planting dates should be undertaken for hemp to determine the month that simulates the highest biomass, seed and fibre yields, as was undertaken by Lake (2024).

According to Lake (2024), cowpea is considered the best calibrated crop amongst 10 neglected and underutilised crops, whereas bambara nut is the best validated. Lake (2024) completed national AquaCrop runs for both crops, each with four planting months (October to January). The planting month that produced the highest cowpea yield is shown in Figure 6-19, where the central and eastern regions of the country are better suited to cowpea plantings in November and December. However, it is important to note that AquaCrop cannot account for daylength, which is important for photoperiod sensitive plants like cowpea, bambara nut and hemp.

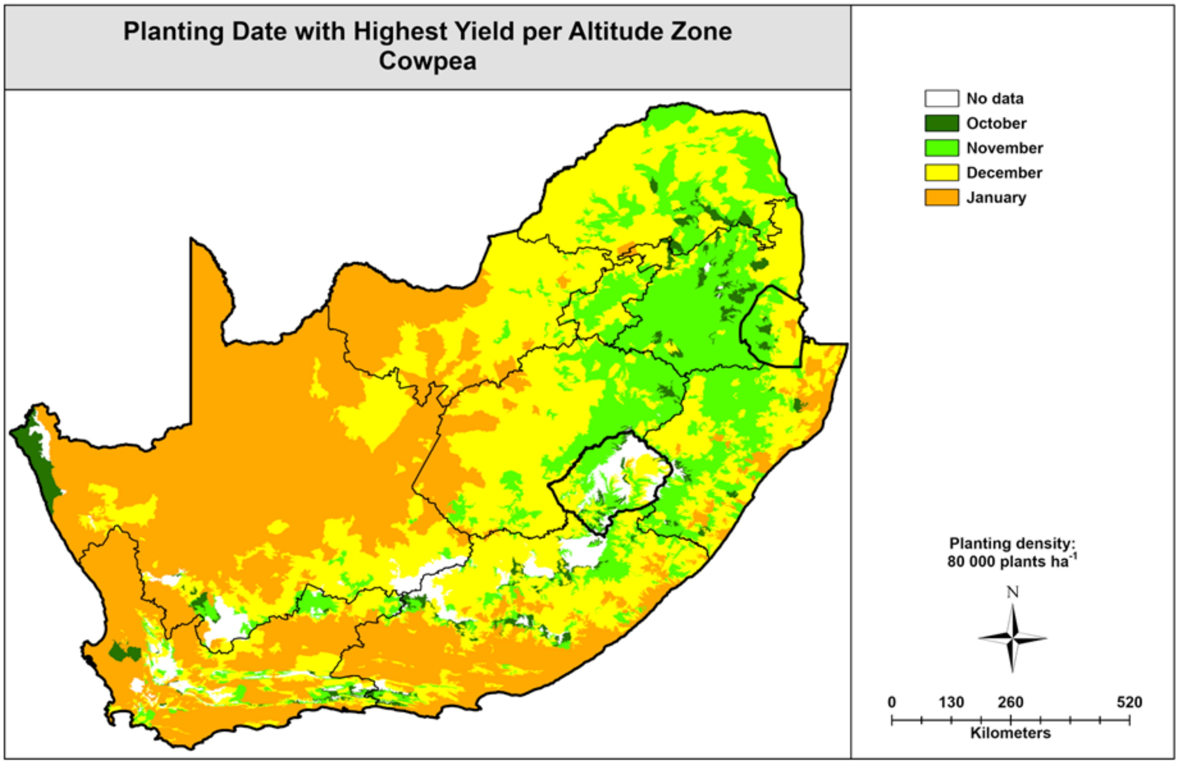

Figure 6-19 Planting date that produced the highest simulated yield for cowpea per altitude zone (Lake, 2024)

6.1.4 Conclusions and recommendations for future research

<u>Assumptions and limitations</u>: It was assumed that the crop parameter files developed by Wimalasiri et al. (2021b) with data for Italy are applicable to hemp fibre and seed production in South Africa. Wimalasiri et al. (2022) made a similar assumption when they applied their crop parameter files to estimate fibre and seed yields in Malaysia. Since the experimental work undertaken in this project focused solely on floral bud production, measurements and observations could not be used to fine-tune the crop parameter files.

Only one planting month (December) was considered, with two planting densities representing fibre and seed production systems. Hence, hemp floral (bud) yield was not simulated since the required crop parameter file does not exist. The final plant density was assumed to be the same as the initial density since male plants were not removed. The male plants were allowed to pollinate the female plants, resulting in seed production. The simulations therefore represent plants grown outdoors under rainfed conditions, at a scale large enough to achieve profitability.

It is important to re-iterate that AquaCrop was run in calendar day mode, as was done by Wimalasiri et al. (2022). AquaCrop does not account for pests and disease impacts on crop growth. Hence, hemp yields (seed, fibre and biomass) were lover-estimated, including crop cycle length and CWP, because transpiration is not reduced by cold temperature stress, nor does hot/cold temperature stress inhibit pollination or decrease HI. A very low number of seasons with zero yield (i.e. crop failures) were simulated as a result of running AquaCrop in calendar day mode. Therefore, the maps of seed yield and biomass production are more useful in showing relative differences between altitude zones than actual values likely to be attained in each zone.

<u>Recommendations for future work</u>: Field experiments should be conducted in the future to estimate (i) seed yield, (ii) fibre yield, and (ii) accumulated biomass. Such experiments should consider both (i) irrigated (i.e. non-stressed), and (ii) rainfed (i.e. stressed) growing conditions. Measurements of LAI and biomass production should be conducted over the growing season, including final biomass and seed/fibre yield at harvest. Ideally, the experiments should be repeated across different agro-ecological zones deemed suitable for hemp production.

The data collected from field experiments can then be used to re-calibrate and validate the crop parameter files used in this project to improve the confidence in model simulations. Furthermore, observations of crop phenology in calendar days should be converted to GDDs, allowing AquaCrop to be run in GDD mode, which provides more realistic simulations of crop growth, yield and water use. The number of zero yield simulations should be used to calculate the risk of crop failure, which defined as the number of zero yields divided by the number of simulated seasons, expressed as a percentage.

Attempts were made to obtain the daily temperature file used by Eranga Wimalasiri for the calibration of hemp for fibre and seed yield. This would allow for the conversion of phenological growth stages from calendar days to growing degree-days. Since the calibration data was collected in Piacenza (Italy), the suggestion is made to contact Dr Stefano Amaducci and Dr Martina Leoni to help obtain data for 2014 and 2015.

Future model simulations for hemp should consider five planting months from September to January. Although this significantly increases computational complexity, it allows for the development of maps showing the planting month that produced the highest yield in each altitude zone. Such information is useful for developing production guidelines for *C. sativa*.

The seed and biomass yield maps produced in this project provide some indication of which AZs might be considered as marginal for hemp production. However, it is more difficult to determine which zones are considered totally unsuitable for hemp cultivation. If AquaCrop is grown in GDD mode, Kunz et al. (2024) successfully demonstrated the use of AquaCrop output for identifying AZs deemed unsuitable for production of sweet potato and taro. Future work should therefore consider using AquaCrop simulations to develop land suitability maps for the cultivation of hemp biomass, fibre, seed and floral buds.

For floral production, the plant population is thinned during the pre-flowering stage to remove male (or dual-sex) plants to prevent pollination of female plants. Hence, the final plant density is always less than the initial density and the plants do not senesce or reach physiological maturity. These plants are typically grown in greenhouses or indoors under artificial light, especially to prevent wind pollination by nearby plants grown for seed (or fibre) yield. Since floral production is very different to biomass, fibre and seed production, a separate crop parameter file should be developed for floral production. The parameter called “crop determinancy” should be set to 1 (i.e. linked with flowering), which indicates hemp is a determinate plant where the vegetative growth period stops at peak flowering (i.e. halfway through the flowering period). In contrast, the vegetative growth period stretches from sowing till canopy senescence for indeterminant plants. Important parameters to adjust include the time from sowing/transplanting to the start of flowering, including the length of the flowering period. The time to senescence should match the end of the flowering period. The time to maturity should match the time to senescence. Other important parameters to calibrate will be the "possible increase (%) of HI due to water stress before flowering", and the "building up of HI starting at flowering" period. The latter represents the time required for HI to increase from 0 (at flowering) to its reference value (HI_O) under optimal conditions. Typically, HI reaches HI_O at or shortly before maturity (Raes et al., 2018). HI_O should be calculated as the ratio of bud yield to biomass production. The plant density should be set to the final value at harvest to reflect the removal of male (or dual-sex) plants to prevent pollination and seed formation.

Future work should consider conducting an analysis of economic viability of hemp production in South Africa. Hemp's stem, which contains bast fibre, is of greater economic value than its woody core (for bioenergy). A cost-benefit (or break-even) analysis should be done by comparing input costs (e.g. seed, fertiliser, labour, water and land) versus benefits (income from sale of fibre, seed and/or floral buds). For example, Wimalasiri et al. (2021b) calculated a minimum economically viable yields of 1.38 and 3.62 t ha^{-1} for seed and fibre production in Malaysia, respectively. The analysis will also need to factor in security costs related to fencing and alarm systems, which are required by law to protect the crop.

6.2 Hydrological modelling and impacts

6.2.1 Introduction

This section provides the methodology used to assess the potential impact of rainfed hemp biomass production downstream water availability (aim 4 of the project). The ACRU hydrological model (Schulze, 1995; Smithers and Schulze, 1995) was used to determine catchment runoff for both natural vegetation and for hemp. The difference in runoff generation between the two land covers was then used to assess if hemp biomass production is a potential stream flow reduction activity (SFRA).

Use of the ACRU hydrological model to assess potential SFRAs has been accepted by DWS (Clulow et al., 2023), since the model has been extensively used and verified in South Africa and abroad (Schulze, 2023). For example, ACRU was used in recent SFRA studies to assess the potential impacts of the following land covers on downstream water availability:

a) two potential biofuel crops, namely sorghum and soybean (Kunz et al., 2020),

b) three bamboo species (Everson et al., 2021),

c) 15 commercial forestry species/clones/clones (Clulow et al., 2023), and

d) two root and tuber food crops, namely sweet potato and taro (Kunz et al., 2024).

6.2.2 Methodology

6.2.2.1 Model description

ACRU is a physical model where processes are represented explicitly with initial and boundary conditions. ACRU is also a conceptual model where important processes are coupled (Figure 6-20), and thus is considered a physical-conceptual model of intermediate complexity. Total evaporation from the vegetated surface consists of both soil surface evaporation (E) and transpiration (Tr), which is governed by rooting patterns. These two processes are typically modelled separately.

When modelling the vegetation layer in ACRU (Figure 6-20), four processes are considered, namely canopy interception loss, evaporation from the canopy (of transpired and intercepted water), evaporation of water from the soil surface and soil water extraction by plant roots (to quantify transpiration).

During periods of sustained plant stress, when the soil water content of both the upper and lower soil horizons falls below 40% (for example) of plant available water, transpiration losses are reduced in proportion to the level of plant stress. When plant available water increases to above 40% in either soil horizon, plant stress is relieved and the evaporative losses recover to the optimum value, at a rate dependent on the ambient temperature. In ACRU, runoff response variables are used to govern the portion of storm flow exiting a catchment on a particular day (as quick flow), as well as the portion of base flow originating from the groundwater store, which contributes to runoff generation (Schulze, 1995).

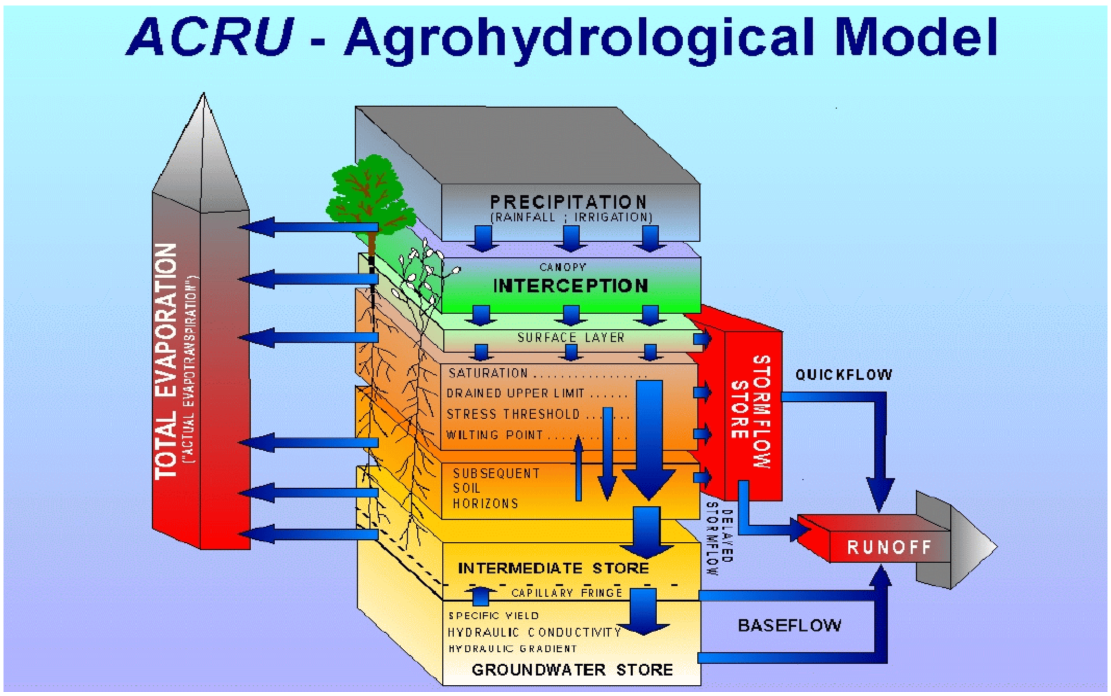

Figure 6-20 Structure of the ACRU hydrological modelling system (Schulze, 1995)

ACRU operates at a daily time step, therefore making optimal use of available climatic information, and thus is suitable in terms of flow regimes and sediment yield, which are highly correlated with individual rainfall events (Schulze, 1995). The model is sensitive to changes in land cover, land use and land management that impact runoff response. Hence, ACRU has been frequently used to assess the impacts of land use change and climate change on:

- storm flow, base flow and total runoff from each catchment,
- accumulated daily stream flow from all upstream catchments,
- peak discharge, sediment yield and recharge to groundwater, and
- daily soil water content and evapotranspiration.

6.2.2.2 Model inputs

6.2.2.2.1 Soil data

ACRU also utilises the Altitude Zones Soil Database (cf. Section 6.1.2.2.1) to obtain soil water retention parameters and depth values for both the A-and B-horizon in each AZ. In addition, two other ACRU parameters, namely *ABRESP* and *BFRESP*, were also derived for each AZ (Schulze and Schütte, 2023). These represent the fraction of "saturated" soil water that is redistributed each day from the topsoil into the subsoil (*ABRESP*), and from the subsoil into the intermediate/groundwater store (*BFRESP*).

For the majority (5 244 of 5 838 or 89.8%) of the AZs, the depth of the A-horizon (*DEPAHO* in ACRU) is below 0.25 m (Figure 6-21), with the average being 0.18 m (0.01-0.30 m range). Similarly, the depth of the B-horizon (*DEPBHO* in ACRU) is below 0.50 m (Figure 6-22) for 92.9% of the AZs, with the average being 0.26 m (0.01-0.90 m range).

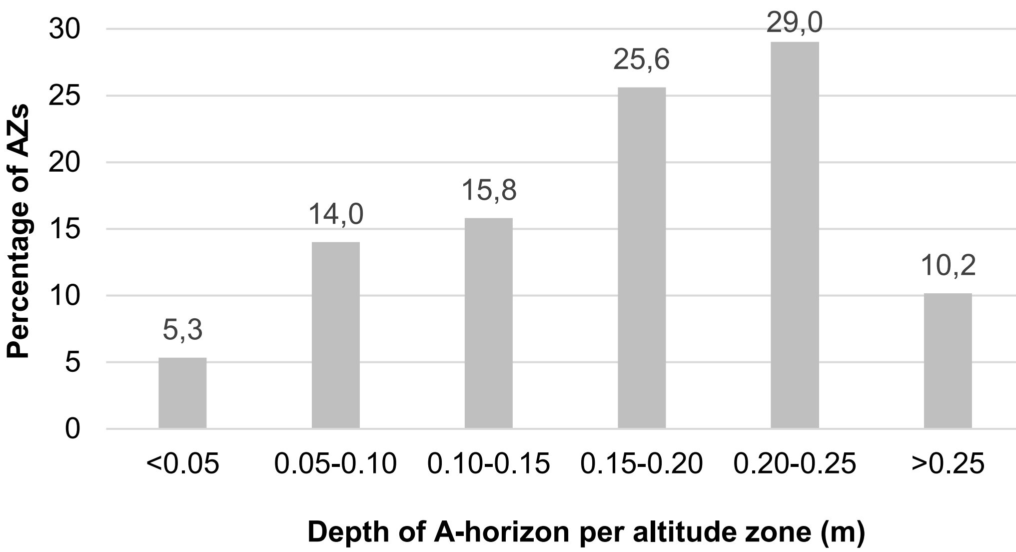

Figure 6-21 Range in depth of the A-horizon per altitude zone

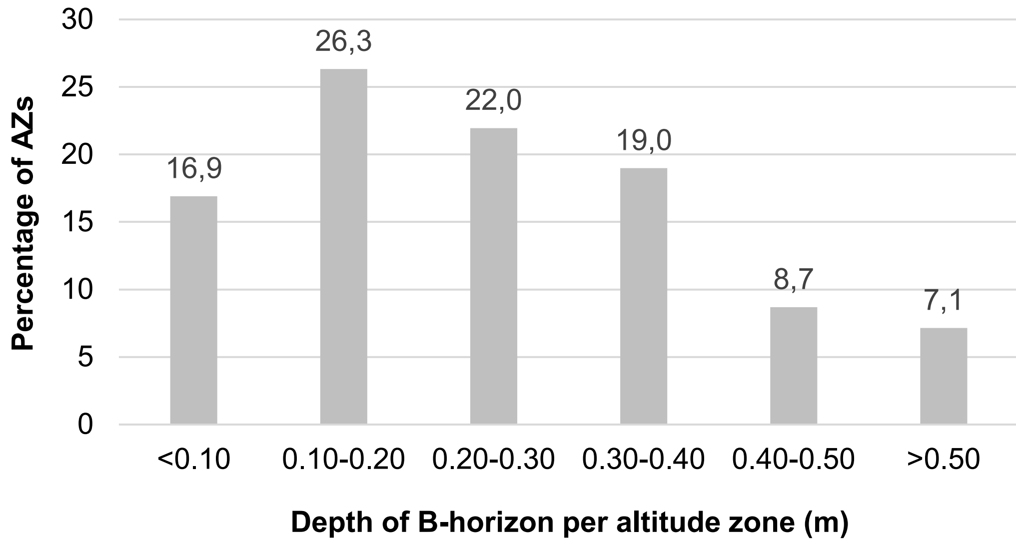

Figure 6-22 Range in depth of the B-horizon per altitude zone

6.2.2.2.2 Climate data

Daily climate data required to run ACRU was obtained from the Altitude Zones Climate Database (cf. Section 6.1.2.2.2). However, ACRU requires A-pan equivalent reference evaporation (E_{PAN}), and thus reference evapotranspiration (ET_O) values must be adjusted using monthly pan coefficients. This was done in ACRU using the monthly *CORPAN* parameters (cf. Section 6.2.2.2.3).

Monthly pan coefficients (*CORPAN*) were calculated by Kunz et al. (2015) for each AZ as E_{PAN}/ET_O. Pan coefficients are always greater than unity (i.e. 1), especially during the winter months, since $E_{PAN} > ET_O$ by a factor of 1.16 to 1.51. These monthly adjustment factors were based on a modified version of the PenPan equation, which was developed in Australia to estimate E_{PAN}, then applied to each AZ. For more detail, refer to Kunz et al. (2015).

6.2.2.2.3 Model parameters - Rainfall:runoff response

Most of the ACRU input parameters that represent rainfall:runoff response and the vegetation layer (cf. Figure 6-20) are physically based, and thus are measurable (Smithers and Schulze, 1995), which implies the model requires little calibration. Therefore, ACRU is not a model in which parameters are calibrated to produce a good fit between observed and simulated stream flow. However, some parameters are more difficult to measure than others. Key parameters in ACRU that influence runoff generation are shown in Table 6-10, together with their brief description. Sensitivity analyses (e.g. Angus, 1989; Toucher et al., 2020) indicate that ACRU is most sensitive to changes in rainfall input (*CORPPT*) and highly sensitive to changes in certain parameters such as *SMDDEP* (Table 6-10).

The derivation of monthly rainfall adjustment factors (*CORPPT*) so that the driver rainfall station is deemed more representative of each AZ was discussed previously in Section 6.2.2.2.2. Similarly, determination of monthly ET_O to A-pan evaporation adjustment factors (*CORPAN*) was also discussed in Section 6.2.2.2.2. The effective rooting depth (*EFRDEP*) is assumed to be the total soil depth, i.e. the sum of the A-horizon (*DEPAHO*) and B-horizon (*DEPBHO*) depths for each AZ. The remaining four parameters in Table 6-10 are difficult to measure, and thus values were obtained from previous ACRU studies that best represent the scale of the AZs. For example, Kunz et al. (2020) set *SMDDEP* to the thickness of the topsoil as suggested by Smithers and Schulze (1995). *COIAM* typically varies from 0 to 0.35 (default of 0.20) and unique monthly values were determined for each AZ by Kunz et al. (2020) using rainfall seasonality and distance from the coastline. The same *COIAM* vales were used for the baseline (natural vegetation) and cannabis model runs.

Table 6-10 Key parameters in ACRU that influence rainfall:runoff response

Variable	Definition	Value	Reference
CORPPT	Monthly precipitation adjustment factors (e.g. to account for differences in monthly rainfall between the selected driver station and spatially averaged estimates for the altitude zone)	Monthly	Section 6.2.2.2.2
CORPAN	Monthly A-pan adjustment factors (e.g. to adjust Penman-Monteith evaporation estimates to A-pan equivalent evaporation for each altitude zone)	Monthly	Section 6.2.2.2.2
EFRDEP	Effective soil depth for colonisation by plant roots	DEPAHO + DEPBHO	Smithers and Schulze (1995)
SMDDEP	Effective soil depth from which storm flow generation takes place	DEPAHO	Kunz et al. (2020)
QFRESP	Storm flow response fraction for the catchment	0.30	Schulze (2011)
COFRU	Base flow recession constant, i.e. fraction of daily groundwater store that is released as base flow	0.009	Warburton et al. (2010)
COIAM	Coefficient of initial abstraction that accounts for vegetation, soil surface and climate influences on storm flow generation	Monthly	Kunz et al. (2020)

6.2.2.2.4 Model parameters - Land cover/use

Key parameters that account for land cover/use are shown in Table 6-11. Sensitivity analyses (e.g. Angus, 1989; Toucher et al., 2020) indicate that ACRU is most sensitive to *CAY* (Table 6-11), and thus this parameter must be determined as accurately as possible. Water use of the vegetation layer is defined as the difference in runoff generated from the proposed land use (e.g. *Cannabis sativa* production) to that generated by the baseline land cover (e.g. natural vegetation). Thus, to determine the hydrological impact of a land use change to hemp production, it is necessary to first define the baseline vegetation against which water use comparisons are made.

Table 6-11 Key parameters in ACRU that account for land cover/use (Smithers and Schulze, 1995)

Parameter	Definition
CAY	A monthly consumptive water use (or "crop") coefficient, which reflects the ratio of water use by vegetation under conditions of freely available soil water to the evaporation from a reference surface (e.g. ET_O or E_{PAN})
ELAIM	Monthly LAI values that are used to calculate monthly interception losses and/or to determine the crop's consumptive water use
VEGINT	Monthly interception loss values that estimate the magnitude of rainfall that is intercepted by the plant's canopy on a rainy day
ROOTA	The fraction of plant roots that are active in extracting soil moisture from the A-horizon in a given month
EFRDEP	Effective rooting depth
CONST	Fraction of plant available water at which plant stress sets in
FOREST	Simulation of enhanced wet canopy evaporation
PCSUCO	The percentage of the soil surface covered by a mulch or litter layer, which suppresses soil water evaporation
COLON	Extent of root colonisation in the B-horizon, which determines the amount of water that may be extracted by the plant from the subsoil

6.2.2.2.5 Baseline land cover: natural vegetation

In the past, the South African Department of Water and Sanitation (DWS) supported and accepted the use of the 72 veld types identified by Acocks (1988) to represent natural vegetation as the reasonable standard or reference land cover against which impacts of land use change were assessed. In 2019, DWS adopted the vegetation clusters derived by Toucher et al. (2020) as the new baseline against which all potential SFRAs should be assessed. To date, this new baseline has been used by four recent SFRA studies (cf. Section 6.2.1). The updated ACRU model parameters were developed by Toucher et al. (2020) in a transparent and reproducible manner, and thus replace those derived for each Acocks veld type.

In essence, Toucher et al. (2020) used the 2012 vegetation map produced by the South African National Botanical Institute (SANBI) as the new hydrological baseline. This map identifies 435 vegetation types, which were simplified into 121 hydrologically relevant vegetation groupings called clusters. Parameters required by ACRU to determine the water use of each vegetation cluster were determined using remote sensing of monthly leaf area index (*ELAIM*), which were then used to derive monthly crop coefficients (*CAY*). Monthly *ELAIM* was also used to estimate monthly interception loss values (*VEGINT*) using the von Hoyningen-Huene (1983) equation. *ROOTA* estimates were obtained from existing root distribution profiles extracted from the available literature. Monthly *PCSUCO* values were estimated from *CAY* via an S-shaped curve developed by Toucher et al. (2020). *COLON* was estimated using the effective rooting depth (*EFRDEP*) calculated for each vegetation cluster. Owing to the difficulty in deriving *CONST* values for each vegetation cluster, a default value of 0.40 (representing 40% of plant available water) was selected.

6.2.2.2.6 Proposed land use: hemp

CAY: As previously mentioned, *CAY* is an important ACRU model input that is used to estimate water use of the vegetation layer. ACRU is highly sensitive to changes in *CAY* and slightly sensitive to changes in both *ROOTA* and *VEGINT*. It is therefore important to accurately determine representative crop coefficient values for hemp. Monthly *CAY* values should be derived for standard (i.e. non-stressed) growing conditions.

Monthly *CAY* values ranging from 0.56-0.77 were determined by Denton (2024) from eddy covariance measurements of maximum crop evapotranspiration (ET_C) under optimal (rainfed with supplemental irrigation) conditions at Kenlei Farms (KwaZulu-Natal). However, they represent "static" values for a single location and for only one season, and thus may not be representative of other cannabis growing areas. Furthermore, the measured *CAY* values represent the production of floral buds, which is likely to have far less environmental impact when compared to hemp biomass production. For this reason, the AquaCrop model was used to generate monthly *CAY* values unique to each AZ.

For this project, AquaCrop was run for both rainfed and irrigated growing conditions. The rainfed model runs provided estimates of attainable fibre and seed yield as well as biomass production and actual water use (ET_A) for stressed growing conditions. From the irrigated runs, maximum water use (ET_C) was simulated for each AZ, from which monthly *CAY* values were derived as the ratio of ET_C to ET_O. This methodology was used by a) Kunz et al. (2020) for sorghum and soybean, and b) Kunz et al. (2024) for sweet potato and taro. AquaCrop was used to estimate hemp's irrigation water requirement, where irrigation water was added to the soil profile to artificially relieve crop water stress, which was assumed to occur when the soil water content drops below a certain percentage of plant available water (determined by *CONST*).

From the national runs using the fibre and seed crop parameters, the former produced higher monthly crop coefficients from December to April across all AZs, except for AZ number 1 432 and 1 522. Hence, the higher values were utilised in the project to represent the worst-case scenario. From Figure 6-23, the spatially averaged *CAY* value is 0.61 in December, which peaks in February at 0.96. then drops to 0.41 in April. The peak value is due to K_{CB} being 0.96 (Table E-1; line no. 35) since the majority of the soil surface is covered by vegetation (CC_X is 85-90%; line no. 50 in Table E-1).

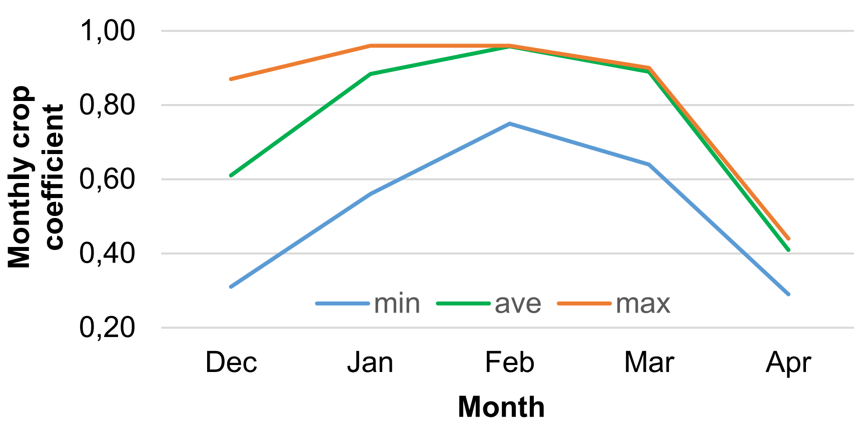

Figure 6-23 Range in monthly crop coefficients derived from AquaCrop simulations of maximum water use for hemp biomass production

For the fallow period, *CAY* values representing weed-free (i.e. bare soil) and weedy conditions have been developed (Table 6-12) from eddy covariance measurements undertaken at Baynesfield and

Fountainhill (KwaZulu-Natal), respectively. For this project, the weedy *CAY* values were utilised to better represent smallholder farming conditions, where the values for October and November were interpolated (not measured).

Table 6-12 Monthly crop coefficients estimated for the fallow period for weed-free (Baynesfield) and weedy (Fountainhill) conditions

Location	Year	May	Jun	Jul	Aug	Sep	Oct	Nov	Reference
Baynes-field	2017	0.26	0.15	0.10	0.18	0.22	0.40		Kunz et al. (2020)
Fountain-hill	2021/22	0.38	0.26	0.20	0.27	0.29	0.44	0.62	Kunz et al. (2024)

ACRU uses the A-pan as its reference evaporation standard (E_{PAN}). Hence, ACRU requires monthly *CAY* values calculated using E_{PAN}. Since *CAY* values for cannabis were based on ET_O, they require adjustment. *CAY* values obtained from AquaCrop for irrigated conditions were therefore multiplied by the inverse of the monthly *CORPAN* values determined for each AZ (cf. Section 6.2.2.2.2). The averaged initial, peak and end-season *CAY* values decreased to 0.46, 0.71 and 0.30, respectively.

ELAIM: Measurements of LAI (*ELAIM*) obtained from the field experiments undertaken in the Eastern Cape (Firglen Farm) and KwaZulu-Natal (Kenlei Farms) could not be used, since they represented floral bud production, not biomass, fibre or seed production systems. At Firglen Farm (Eastern Cape), LAI peaked at ~5 $m^2\ m^{-2}$ on 3rd of January 2023 in section D (not fertilised, planted on contour), whereas LAI peaked at ~0.89 $m^2\ m^{-2}$ in the south and north field at Kenlei Farms (KwaZulu-Natal), respectively. LAI measurements at Kenlei Farms were initially affected by high weed loads, then later by the removal of male plants in the south field. The latter also resulted in a low plant density (1 035 plants ha^{-1}) at harvest. In contrast, Drastig et al. (2020) observed LAI values between 0.6 and 8.8 depending on the hemp cultivar. Tang et al. (2017) reported LAI values of 2.3 and 6.4 $m^2\ m^{-2}$ at full flowering due to nitrogen fertilisation levels of 0 and 120 kg N ha^{-1}, respectively. Hence, LAI for the highest fertilisation rate was three times larger than the control treatment.

Averink (2015) used a peak LAI of 4.25 $m^2\ m^{-2}$ to estimate CC_X. CC_X values of 0.85 and 0.90 for hemp seed and fibre production (Wimalasiri et al., 2021b; cf. Table E-1) correspond to LAI values of 2.12 and 2.53 $m^2\ m^{-2}$, respectively. These LAI values were derived using the equation provided by Hsiao et al. (2009) with *k* set to 0.96. It was assumed that the *ELAIM* curve matches the *CAY* curve as shown in Figure 6-24, i.e. *ELAIM* peaks at 2.53 $m^2\ m^{-2}$ when *CAY* reaches 0.96. Hence, monthly *ELAIM* values unique to each AZ were derived from the product of *CAY* and the constant 2.64 (or 2.53/0.96).

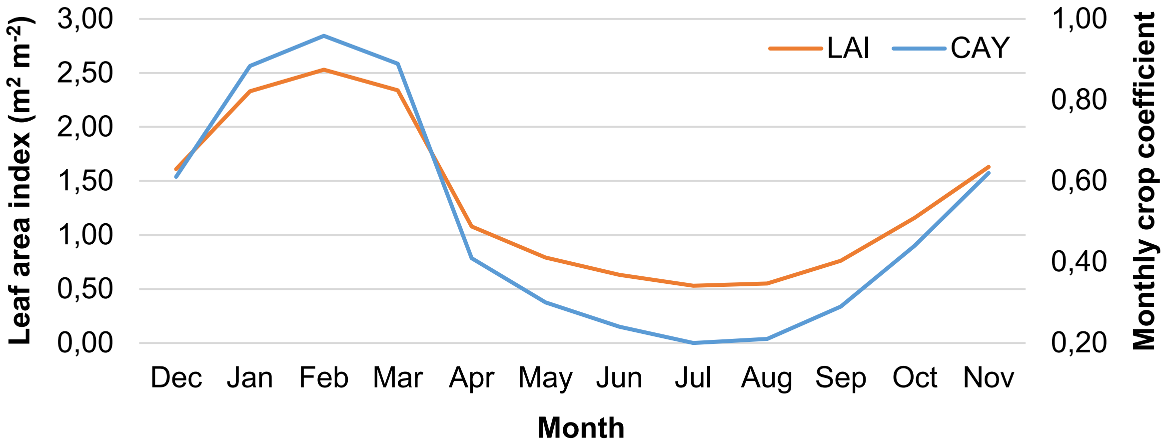

Figure 6-24 Relationship between leaf area index and the crop (or water use) coefficient for hemp biomass production

<u>*VEGINT*</u>: Daily interception loss in mm per rain day (I_C in mm) for hemp was estimated using the von Hoyningen-Huene equation (Von Hoyningen-Huene, 1983), which requires monthly *LAI* (or *ELAIM*) and gross daily rainfall (P_g in mm):

$$I_C = 0.30 + 0.27P_g + 0.13LAI - 0.013P_g^2 + 0.0285P_g \cdot LAI - 0.007LAI^2 \quad [6.1]$$

This method is only "stable" for daily P_g values up to 18 mm. Hence, P_g is "capped" at 18 mm, and thus produces lower estimates of I_C during the summer months. The above equation is built into ACRU and requires representative monthly *ELAIM* values as input for the national model runs. The ACRU parameter *LAIND* was set to 1 to indicate monthly *ELAIM* values were available for each AZ. To utilise the Hoyningen-Huene equation for estimating *VEGINT*, the ACRU parameter *INTLOS* was set to 2. The monthly *VEGINT* values in ACRU's input file (called menu) were set to 0 since daily values were generated during the model run.

<u>*ROOTA*</u>: ACRU requires monthly values of the fraction of active roots in the topsoil horizon (*ROOTA*), from which the fraction in the lower soil horizon is computed internally (i.e. 1 – *ROOTA*). Maximum rooting depth was not observed at Kenlei Farms during the 2022/23 experiment, and thus was obtained from the literature.

Amaducci et al. (2008b) conducted hemp field experiments in northern Italy (44°33'N, 11°21'E, 32 m) over two years. Roots were found at depths of 2.0 m (2004) and 1.3 m (2005), with a total root biomass values of 3.21 and 2.41 t ha^{-1}, of which the tap root accounted for 1.38 and 1.01 t ha^{-1}. Meijer et al. (1995) reported a similar value of 1.10 dry t ha^{-1} of hemp's tap root. Žydelis et al. (2022) observed hemp roots extending to 1.2 m from field experiments carried out from 2019 to 2021 in central Lithuania (55°40'N, 23°86'E, 65 m). Amaducci et al. (2008b) stated that root length density was highest in the first 10 cm of soil and 50% of the total root biomass (including the tap root) was found in the top 50 cm of soil (Figure 6-25).

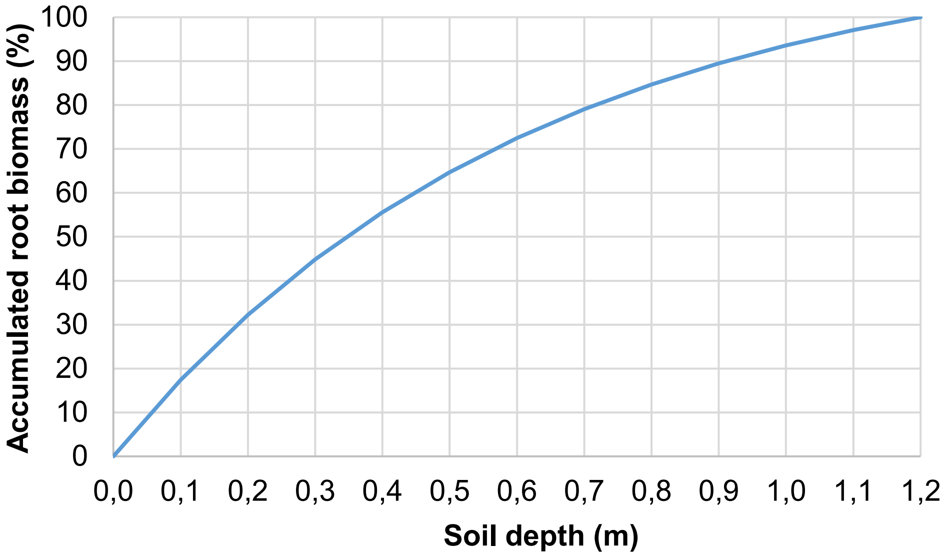

Figure 6-25 Accumulation of total root biomass with soil depth (scaled to a maximum depth of 1.2 m; after Amaducci et al., 2008b)

DEPAHO was used to determine *ROOTA* based on the relationship shown in Figure 6-25. Hence, *ROOTA* ranged from 0.02-0.45 (average of 0.28). The same value was used for December to April. For the fallow period (May to November), *ROOTA* was set to unity, thus indicating that transpiration from weeds (and soil water evaporation) takes place from the topsoil only. Toucher et al. (2020) noted that setting *ROOTA* to 1 can result in large increases in simulated stream flow.

EFRDEP: The effective root depth (*EFRDEP*) in ACRU determines the depth of soil which is "active" in the soil water budget, from which roots can extract water. By default, *EFRDEP* is set to the total depth of both soil horizons (i.e. *DEPAHO* + *DEPBHO*). Since information on impeding layers (for root development) within the soil profile does not exist nationally, *EFRDEP* was not altered for the cannabis model run.

CONST: This parameter represents the onset of plant water stress and is difficult to measure, and thus the default value of 0.40 was used for the baseline land cover (i.e. all vegetation clusters). Allen et al. (1998: p 163-165) provided values for the soil water depletion fraction (*p*) for a range of crops, which represents the fraction of plant available water that can be depleted before moisture stress occurs. Hence, *p* is equivalent to 1 - *CONST*.

Hemp has a well-developed and deep root system, which allows the plant to withstand moderate drought conditions, provided the crop is planted in deep soil (Struik et al., 2000; Gill et al., 2023). According to Morgan et al. (2024), two hemp cultivars were grown in a greenhouse (Carolina, USA) in 2021 and 2022. Floral (bud) yield, THC and CBD concentrations were not affected by moderate stress (30-50% of field capacity), which started at flowering. However, extreme water stress (0-10% of FC) significantly reduced floral, THC and CDB yield. Sebastian et al. (2023) stated that claims of drought tolerance for hemp production (floral, seed and fibre) are unfounded, considering hemp requires about 20% more irrigation than cotton for economic fibre yield. In contrast, a review of 28 journal papers by Wise et al. (2023) showed that hemp has a 38% lower crop water requirement and a 60% lower water footprint when compared to cotton. Tang et al. (2017) found that drought during the seed filling stage resulted in reduced seed accumulation and seed mass.

Owing to the conflicting evidence regarding hemp's drought resistance (e.g. Gill et al., 2023; Sebastian et al., 2023), the assumption was made that hemp is similar to other fibre crops such as cotton and flax. For both crops, Pereira et al. (2021) provided *p* values of 0.60 and 0.50 respectively, which are similar to values of 0.60 for sugarcane and 0.55 for barley. Hence, *p* was set to 0.55 for hemp (i.e. *CONST* = 0.45).

FOREST: If half of the catchment area is afforested, The *FOREST* option is invoked (i.e. set to 1) in ACRU to simulate enhanced evaporation from the wet canopy. For natural vegetation, this occurs in 247 AZs. For cannabis production, *FOREST* was set to 0 (i.e. no enhanced evaporation) for all AZs.

COLON: In ACRU, it is assumed that the topsoil is 100% colonised by roots, i.e. roots can extract all available soil water in the A-horizon. This is valid for hemp since 50% of root biomass (excluding the tap root) was concentrated in the first 0.20 m (Amaducci et al., 2008b). According to Amaducci et al. (2008b), root dry matter was highest (~240 kg ha^{-1}) in the first 0.10 m of soil, then decreased by half (~120 kg ha^{-1}) at 0.30 m and remained relatively constant till 0.80 m. It then declined sharply to ~50 kg ha^{-1} at 1.2 m. Root diameter was lowest in the top 0.10 m of soil, then increased linearly up to 0.60 m and remained relatively constant from 0.60 to 1.10 m Amaducci et al., 2008b).

COLON reflects the extent to which the subsoil is colonised by roots. For the fallow period, *COLON* was set to 0% to limit soil water extraction to the topsoil only. As a general rule, *COLON* increases as *ROOTA* decreases, and thus *COLON* was set as follows:

- 70% if 0.35 ≤ *ROOTA* < 0.45,
- 80% if 0.30 ≤ *ROOTA* < 0.35,
- 90% if 0.20 ≤ *ROOTA* < 0.30, and
- 100% if 0.00 ≤ *ROOTA* < 0.20.

PCSUCO: The percentage of the soil surface covered by mulch, litter and stones (*PCSUCO*) is used in ACRU to suppress soil water evaporation. For the baseline (i.e. natural vegetation), Toucher et al. (2020) estimated monthly *PCSUCO* values from *CAY* via an S-shaped curve. However, from the literature, cannabis rapidly sheds its leaves soon after they senesce (i.e. turn yellow). De Meijer et al. (1995) reported that shed leaves produced 1.5 to 2.0 t ha^{-1} of dry matter. Long term water stress increases leaf senescence and decreases LAI (Žydelis et al., 2022). Thus, *PCSUCO* was set to 0% from December (planting) to March across all AZs. For April (end-season), *PCSUCO* was set to 100% to mimic rapid leaf loss. For the fallow period (May to November), *PCSUCO* was also set to 100% to mimic weeds dying due to frost occurrence.

6.2.3.1 National model runs

6.2.3.1.1 Estimation of runoff

ACRU was run at the national scale to estimate runoff response for all 5 838 AZs, regardless of whether cannabis can successfully be grown in the zone. The following approach was used, which is similar to that used in previous SFRA studies:

- Daily climate data and soils information for each AZ was obtained from the Altitude Zones Climate and Soils Databases and used as input to ACRU (cf. Sections 6.2.2.2.1 and 6.2.2.2.2).
- For the baseline, ACRU input parameters derived by Toucher et al. (2020) for each vegetation cluster (cf. Section 6.2.2.2.5) were used to represent natural vegetation.
- The ACRU model was run to simulate mean monthly and annual runoff (MAR) response for baseline conditions (MAR_{BASE}), i.e. the runoff produced from a land cover of natural vegetation.
- Thereafter, ACRU input parameters were changed to the values given in Section 6.2.2.2.6, which reflect a vegetation layer of hemp biomass.
- Model runs were repeated to estimate MAR for hemp biomass production (MAR_{CROP}), assuming a 100% change in land cover from natural vegetation to crop cultivation.
- Kunz et al. (2024) showed that MAR simulated by ACRU is more sensitive to planting date, rather than plant density. However, only one plant density (150 000 plants ha^{-1}) and one planting date (01 December) were considered in this project to minimise computational complexity.

6.2.3.1.2 SFRA assessment

In the context of assessing stream flow reduction potential, crop water use is defined as the reduction in MAR that may result from a land use change from the baseline (base) to the proposed land use (crop), i.e. MAR_{BASE} - MAR_{CROP}. Although this reduction can be expressed in absolute (i.e. mm) terms, it is more appropriate to consider runoff differences in relative (i.e. %) terms. Hence, the simulated reduction in MAR is expressed as a percentage change relative to the baseline, i.e. $MAR_{REDN} = 100\cdot(MAR_{BASE} - MAR_{CROP})/MAR_{BASE}$.

6.2.3.1.3 Automation process

As part of previous WRC-funded projects, the ability to run ACRU for all 5 838 AZs has been fully automated. Of significant benefit to this project are the improvements made to ACRU by Kunz et al. (2020; WRC Project K5/2491) to optimise the speed at which the model runs, as well as significant changes made to the print and statistics utilities to optimise their computational performance and output format.

For WRC Project No. K5/2833 (Schütte et al., 2023), other significant improvements were made to optimise memory utilisation by the model. This removed the previous limitation where ACRU could only be run for a maximum of 6 000 catchments. Additional “tweaks” were made to further improve model performance by Kunz et al. (2024). The changes made to ACRU have resulted in the model running about 13 times faster than the version used in by Jewitt et al. (2009). In other words, a national run for all 5 838 minutes now takes ~40 minutes, and not 8.5 hours as in 2009.

6.2.3 Results and Discussion

Jewitt et al. (2009) provided the framework for the declaration of a potential SFRA and for the regulation of a declared SFRA. Jewitt et al. (2009) suggested that if MAR_{REDN} is 10% or more, then DWS may declare the land use as a SFRA (Jewitt et al., 2009). At present, commercial afforestation is the only land use declared as a SFRA in Section 36 of the NWA (Jewitt et al., 2009). Similarly, a

25% reduction in low flows can also be considered significant. Low flows are defined as the lowest 25% of the flow regime, or the flow in the driest three months of the year.

6.2.3.1 Impact on annual runoff

Owing to a land use change from natural vegetation to hemp biomass production, altitude zones where MAR_{REDN} may exceed 10% are shown in Figure 6-26. However, not all zones are suited to rainfed production of hemp biomass. For example, hemp production is economically unviable in the drier altitude zones situated in the Northern and Western Cape provinces, including those in the western parts on the North West, Free State and Eastern Cape. Hence, these areas should be excluded. Furthermore, some of the highlighted zones are located within protected areas (e.g. western KwaZulu-Natal near Lesotho border) where commercial (i.e. large scale) crop production is prohibited. When compared to results from SFRA studies for other emerging crops such as bamboo (Everson et al., 2021), sweet potato and taro (Kunz et al., 2024), the cultivation of hemp biomass may significantly reduce stream flow in some areas.

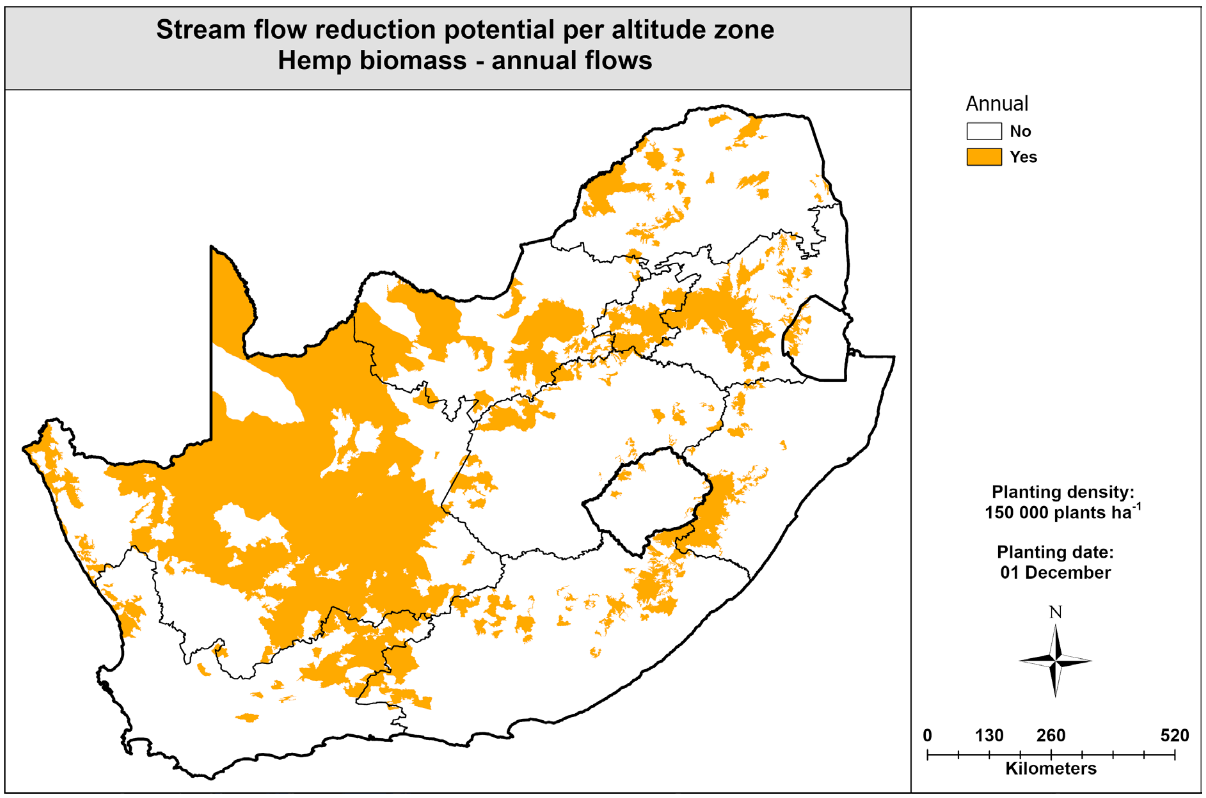

Figure 6-26 Location of AZs where the reduction in mean annual runoff exceeds 10% that could occur due to a land cover change from natural vegetation to hemp biomass production

However, the reduction in annual runoff due to hemp biomass production is likely over-estimated for the following reasons:

- As noted previously, AquaCrop was run in calendar mode, which results in over-estimation of crop ET_C, and similarly *CAY* values. Hence, less runoff will be generated from the hemp crop.

- It is also important to understand that the relative reductions along the eastern seaboard assume a 100% change in land cover from natural vegetation to crop cultivation in each HRZ, which is unrealistic. When assessing SFRA potential, this assumption needs to be considered.
- *ROOTA* was set to 1 during the fallow period, which could result in over-estimation of runoff during the winter period.
- The simulated reductions in runoff represent the worst-case scenario, i.e. biomass production from a high plant density. For seed production, the plant density is halved, and thus crop ET is much lower, resulting in more runoff.

Based on the relatively low crop coefficients (0.56-0.77) determined from eddy covariance measurements at Kenlei Farms, hemp grown for floral (bud) production is unlikely to significantly reduce runoff production when compared to natural vegetation. This is mostly due to the (i) much lower final plant density (removal of male plants), and (ii) shorter growing season since the crop is harvested soon after flowering.

As shown in Figure 6-27, 16.8% of the AZs may experience a significant reduction in MAR that exceeds 10%. For almost half of the AZs, MAR_{REDN} ranges from 2 to 10%, whereas runoff production from hemp is very similar to that from natural vegetation (i.e. $-2 < MAR_{REDN} \leq +2\%$) in 14.2% of the zones. It is also worth noting that compared to natural vegetation, more runoff is produced from hemp in one fifth of the AZs. Hence, the potential reduction in runoff in one catchment can be offset by the water "gain" (when $MAR_{CROP} > MAR_{BASE}$) in neighbouring catchments.

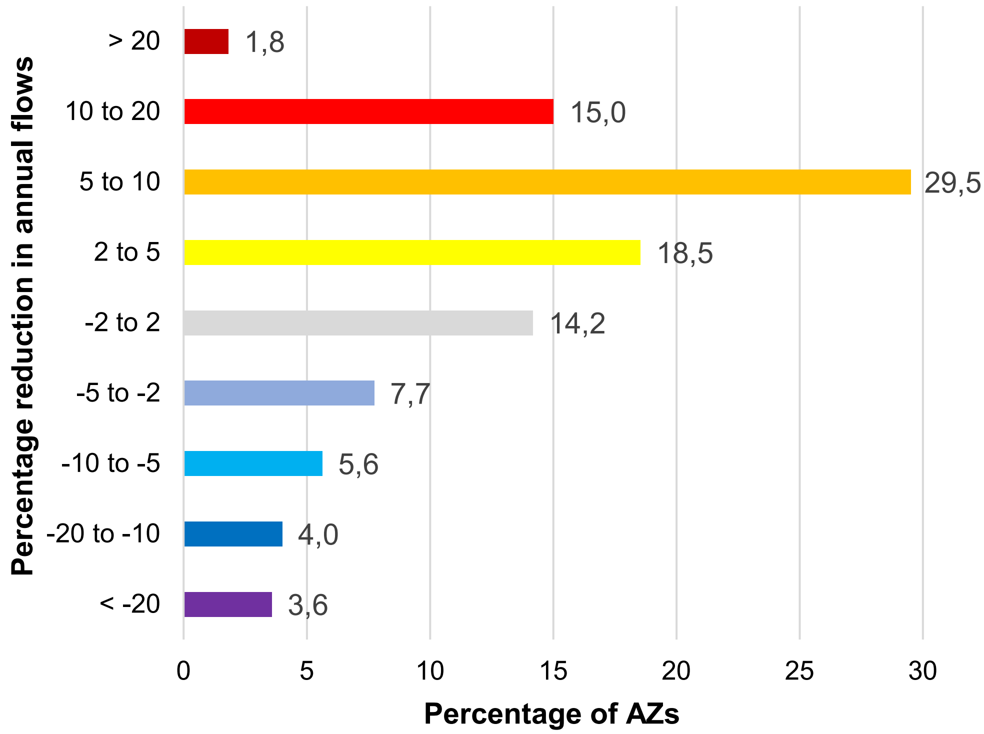

Figure 6-27 Histogram of the percentage reduction in mean annual runoff per altitude zone that may result from a change in land use from natural vegetation to hemp biomass production

In a recent study undertaken by Everson et al. (2021), ACRU was used to assess the SFRA potential of two bamboo species (*B. balcooa* and *B. bema*) using crop coefficients obtained from ET_A measurements in KwaZulu-Natal and the Eastern Cape under rainfed conditions. Crop coefficients for KwaZulu-Natal were higher than those for the Eastern Cape, re-iterating the site-specific nature of *CAY* values. As expected, the higher crop coefficients produced a greater impact on runoff generation since evapotranspiration is greater, which results in reduced runoff, especially in the summer months (Everson et al., 2021).

However, it is important to note that the runoff results simulated by ACRU for bamboo were based on crop coefficients derived from experiments that were rainfed. Thus, the crop coefficients do not represent standard, non-stressed conditions, which are required to estimate maximum crop evapotranspiration and water use. Furthermore, the approach taken by Everson et al. (2021) assumes that *CAY* values obtained at both experimental sites are applicable to all other AZs deemed suitable for crop production, which is not the case. For these reasons, the AquaCrop model was used in this project to estimate a unique set of monthly crop coefficients for each AZ, as suggested by Kunz et al. (2020; 2024).

6.2.3.2 Impact on low flows

Stream flow reductions during the low flow period may be proportionately greater than for annual flows (Scott and Smith, 1997). Hence, a similar analysis was undertaken for mean monthly flows accumulated over the driest quartile (i.e. three months with the lowest runoff response) for hemp biomass production, which were then compared to baseline values. If the percentage difference (relative to the baseline) exceeds 25%, then the reduction is considered significant, as recommended by Jewitt et al. (2009b; cf. Figure 4.1). Such areas are highlighted in Figure 6-28, especially those that occur in the North West, Limpopo and Mpumalanga provinces.

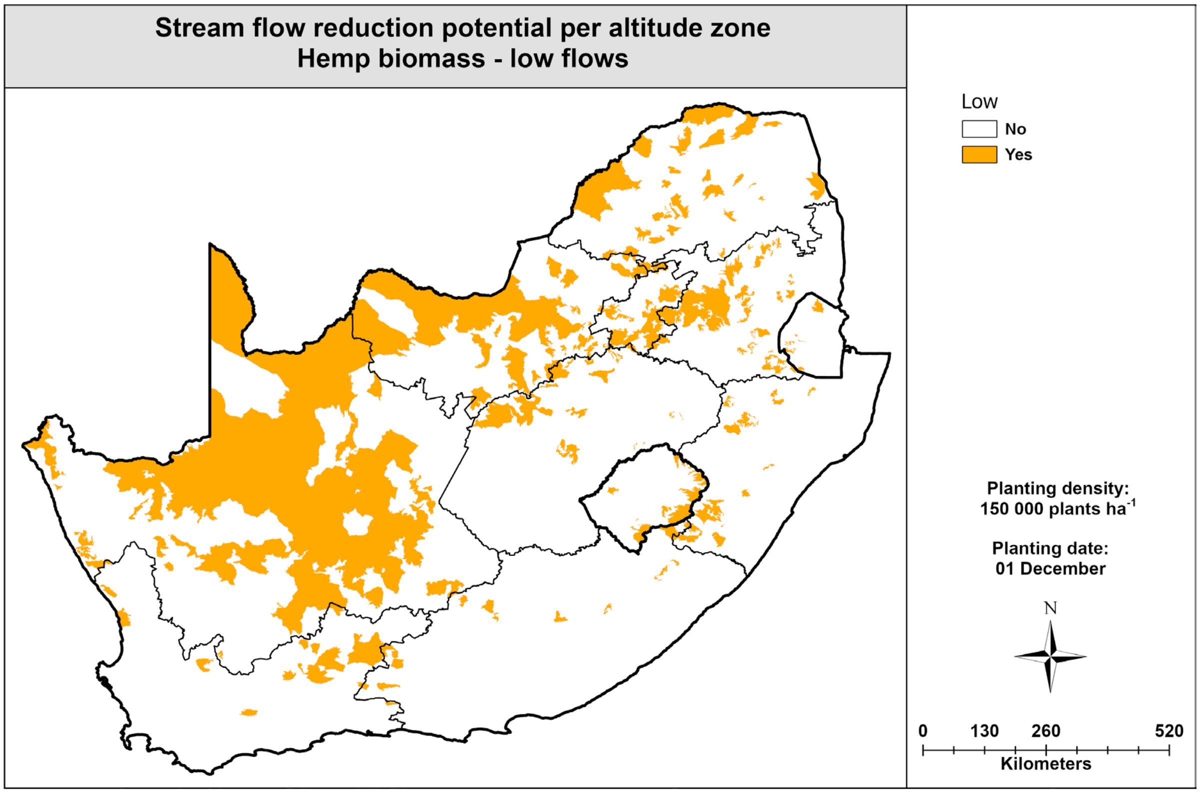

Figure 6-28 Location of AZs where the reduction in runoff during the low flow period exceeds 25%, which may occur due to a land cover change from natural vegetation to hemp biomass production

Runoff in the winter months (i.e. fallow period) was mostly affected by the relatively high crop coefficients representing weedy conditions (not bare soil), which may lead to higher ET and reduced runoff. Hence, to further reduce any potentially negative impact on downstream water availability, farmers should be encouraged to keep their fields weed free during the fallow period.

The reduction in low flow runoff exceeded 25% in ~10% (558 of 5 838) of the AZs. It is important to note that this does not represent 10% of the country's total area since the AZs vary in size. Quaternary catchments are much larger in flatter areas, especially in the western parts of South Africa, as shown in Figure 6-4 (cf. Section 6.2.2.4.1). This explains why the coloured regions in Figure 6-28 do not represent 10% of the country. For almost half of the AZs, the reduction in low flow ranges from 5 to 25%, whereas runoff from hemp in the winter months is very similar to that from natural vegetation (i.e. within ±5%) in one-quarter of all zones.

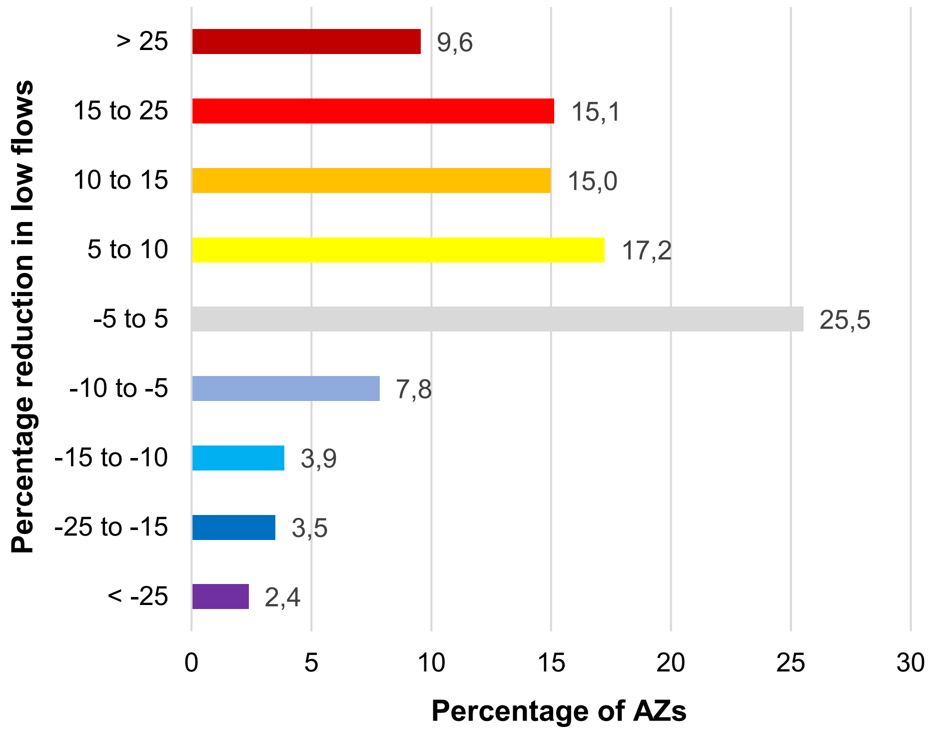

Figure 6-29 Histogram of the percentage reduction in mean annual runoff per altitude zone that may result from a change in land use from natural vegetation to hemp biomass production

6.2.4 Conclusions and recommendations for future research

Increased production of hemp, especially for biomass production, may result in land use changes that have a negative impact on available water resources, even if crops are rainfed. Hence, one of the project's aims was to model the hydrological impact of hemp production on downstream water availability. The ACRU hydrological model was selected since it has been used extensively in many other WRC-funded projects to assess the impact of land use change on hydrological response. ACRU was run at a national scale using climate and soil data currently available for each of the 5 838 AZs. Initial results showed that cultivation of hemp biomass may significantly reduce stream flow in some areas, especially when compared to other emerging crops such as bamboo, sweet potato and taro. Based on initial results, it is recommended that large-scale production of hemp biomass is not conducted in water-stressed catchments. However, this project represents a scoping study that investigated the potential water use and yield of cannabis for the first time. Further research is required to quantify the water use of different hemp production systems.

<u>Assumptions and limitations</u>: It is important to re-iterate that AquaCrop was run in calendar day mode (not growing degree-day mode). This means transpiration is not reduced by cold temperature stress, nor does hot/cold temperature stress inhibit pollination or decrease HI. As a result, the crop cycle length is relatively similar across the entire country, which is unrealistic. In hot environments, the season length is shorter because the crop grows faster, and thus water use and yield are reduced. Hence, the model will over-estimate crop ET resulting in (i) larger crop coefficients, (ii) above-ground biomass production, and (iii) seed/fibre yield.

The crop coefficients calculated from AquaCrop output assume weed-free conditions throughout the crop cycle. Experience has shown that for many smallholder and emerging farmers, manual weeding is not a viable option due to high labour costs. Hence, crop ET during the growing season may be greater than that simulated by AquaCrop.

The crop coefficients for weedy conditions during the fallow period were calculated from ET_A measurements undertaken at only one location for rainfed conditions. The same values were used for all altitude zones across the entire country, which is not ideal.

The approach assumes a 100% change in land cover from natural vegetation to hemp cultivation, which is unlikely to be the case. Hence, hemp's stream flow reduction potential is likely to be over-estimated.

Recommendations for future work: Further research is required to gather more evidence (i.e. measurements) for DWS to declare hemp cultivation as a SFRA. If this evidence conclusively shows hemp is a SFRA, the government will need to limit (i.e. restrict) the spatial extent of hemp cultivation in order to minimise negative impacts on local and regional water resources.

Pereira et al. (2021) reviewed more recent journal papers to update ET_O-based crop coefficients originally published by Allen et al. (1998). The authors found no papers related to K_C values for hemp, jute and sisal. This highlights the need to publish the results presented in Chapters 3-5 of this report.

Future research should focus on utilising AquaCrop to determine crop coefficients from simulated evapotranspiration that represent both (i) weed-free (i.e. bare soil), and (ii) weedy conditions. For the latter, evapotranspiration should be estimated for standard conditions where weed growth is not limited by water availability. The unique set of monthly crop coefficients derived for each AZ should then replace the "static" values (determined for only one location), which were used for all zones.

Rainfall data is a major source of uncertainty in simulation modelling, particularly in arid and semi-arid regions. Since uncertainty typically decreases with increasing number of observations, longer climate records can result in more reliable modelling. Since the climate data for each AZ ends in 1999, it does not reflect the anthropogenically induced changes in extreme climatological events that have occurred over the past 25 years. It is therefore recommended that the Altitude Zones Climate Database is extended with observed daily data by at least 20 years.

Planting date affects model simulations more than plant density. Owing to time constraints, only one planting date was considered (December). Using a variable planting date approach for each AZ is not recommended. Instead, the model should be run for other planting dates, namely September to January. This will provide a better understanding of crop response to planting date.

6.3 References

ACOCKS JPH (1988) *Veld types of southern Africa*. Botanical Survey of South Africa Memoirs 57, Botanical Research Institute, Pretoria, South Africa.

ALLEN RG, PEREIRA LS, RAES D, SMITH M (1998) *Crop evapotranspiration - Guidelines for computing crop water requirements*. FAO Irrigation and Drainage Paper 56, Food and Agricultural Organisation, Rome, Italy.

AMADUCCI S, COLAUZZI M, BELLOCCHI G, COSENTINO SL, PAHKALA K, STOMPH TJ, WESTERHUIS W, ZATTA A, VENTURI G (2012) Evaluation of a phenological model for strategic decisions for hemp (*Cannabis sativa* L.) biomass production across European sites. Industrial Crops and Products **37 (1)** 100-110.

AMADUCCI S, COLAUZZI M, ZATTA A, VENTURI G (2008) Flowering dynamics in monoecious and dioecious hemp genotypes. Journal of Industrial Hemp **13 (1)** 5-19.

AMADUCCI S, SCORDIA D, LIU FH, ZHANG Q, GUO H, TESTA G, COSENTINO SL (2015) Key cultivation techniques for hemp in Europe and China. Industrial Crops and Products **68** 2-16.

AMADUCCI S, ZATTA A, RAFFANINI M, VENTURI G (2008b) Characterisation of hemp (*Cannabis sativa* L.) roots under different growing conditions. Plant Soil **313** 227-235.

ANGUS GR (1989) Sensitivity of ACRU model input. In: *ACRU: Background: Concepts and theory*, SCHULZE RE, Chapter 18, AT18-1 to AT18-21. WRC Report No. 154/1/89, Water Research Commission, Pretoria, South Africa.

AVERINK J (2015) *Global water footprint of industrial hemp textile*. Unpublished MSc dissertation. Water Engineering and Management, University of Twente, Netherlands. https://essay.utwente.nl/68219/

CLULOW AD, KUNZ RP, GOKOOL S, TOUCHER ML, SCHÜTTE S, SCHULZE RE, HORAN R, EVERSON CE, THORNTON-DIBB SLC, HORAN MJC, KAPEIN N, CLARK DJ, GERMISHUIZEN I (2023) *The expansion of knowledge on evapotranspiration and stream flow reduction of different clones/hybrids to improve the water use estimation of SFRA species (i.e. Pinus, Eucalyptus, and wattle species): improved water use estimation of SFRA species – Volume 2: SFRA assessment utility*. WRC Report No. TT 898/2/22, Water Research Commission, Pretoria, South Africa. 212 pp.

COSENTINO SL, RIGGI E, TESTA G, SCORDIA D, COPANI V (2013) Evaluation of European developed fibre hemp genotypes (*Cannabis sativa* L.) in semi-arid Mediterranean environment. Industrial Crops and Products **50** 312-324.

DA SILVA BENEVENUTE S, FREEMAN JH, YANG R (2021) How do pinching and plant density affect industrial hemp produced for cannabinoids in open field conditions? Agronomy Journal **114** 618-626.

DE MEIJER WJM, VAN DER WERF HMG, MATHIJSSEN EWJM, VAN DEN BRINK PWM (1995) Constraints to dry matter production in fibre hemp (*Cannabis sativa* L.). European Journal of Agronomy **4 (1)** 109-117.

DEDECKER J (2019) *Weighing the risk of cannabis cross-pollination*. College of Agriculture and Natural Resources (CANR), Michigan State University (MSU) Extension, East Lansing, Michigan, USA. https://www.canr.msu.edu/news/weighing-the-risk-of-cannabis-cross-pollination

DENG G, DU G, YANG Y, BAO Y, LIU F (2019) Planting density and fertilization evidently influence the fiber yield of hemp (*Cannabis sativa L.*). Agronomy **9 (7)** 368.

DENTON G (2024) Measurement and modelling of *Cannabis sativa* L. evapotranspiration, KwaZulu-Natal Midlands, South Africa. MSc dissertation, Discipline of Agrometeorology, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg.

DRASTIG K, FLEMMING I, GUSOVIUS HJ, HERPPICH WB (2020) Study of water productivity of industrial hemp under hot and dry conditions in Brandenburg (Germany) in the year 2018. Water **12 (11)** 2982.

EVERSON CS, GUMEDE MP, EVERSON TM, CLULOW AD, KUNZ RP (2021) *Quantification of the evapotranspiration and stream flow reduction caused by bamboo species on water resources in South Africa*. WRC Report No. TT/19, Water Research Commission, Pretoria, South Africa.

FOOD AND AGRICULTURAL ORGANISATION (FAO) (2015a) *AquaCrop new features and updates - Version 5.0*. Food and Agricultural Organisation (FAO), Rome, Italy, October 2015. 101 pp.

GARCÍA-TEJERO IF, HERNÁNDEZ A, FERREIRO-VERA C, ZUAZO VHD, GARCÍA JH, SÁNCHEZ-CARNERERO C, CASANO S (2020) Yield of new hemp varieties for medical purposes under semi-arid Mediterranean environment conditions. Comunicata Scientiae **11** e3264.

GARCÍA-VILA M, FERERES E, MATEOS L, ORGAZ F, STEDUTO P (2009) Deficit irrigation optimization of cotton with AquaCrop. Agronomy Journal **101 (3)** 4775-487.

Gill AR, Loveys BR, Cavagnaro TR, Burton RA (2023) The potential of industrial hemp (*Cannabis sativa* L.) as an emerging drought resistant fibre crop. Plant and Soil **493** 7-16.

HIMANSHU SK, ALE S, BELL J, FAN Y, SAMANTA S, BORDOVSKY JP, GITZ DC, LASCANO RJ, BRAUER DK (2023) Evaluation of growth-stage-based variable deficit irrigation strategies for cotton production in the Texas High Plains. Agricultural Water Management **280** 108222.

HSIAO TC, LEE H, STEDUTO B, BASILIO RL, RAES D, FERERES E (2009) AquaCrop - The FAO crop model to simulate yield response to water: III. Parameterization and testing for maize. Agronomy Journal **101 (3)** 4485-459.

KEPHE PH, AYISI KK, PETJA BM (2021) Challenges and opportunities in crop simulation modelling under seasonal and projected climate change scenarios for crop production in South Africa. Agriculture and Food Security **10** 10. 24 pp.

JIANG GCH, CHEN XW, YU J, SUN T (2018) Effects of fertilization pattern and planting density on yield of hemp. Journal of Hunan Agricultural University **44 (1)** 4.

JEWITT GPW, LORENTZ SA, GUSH MB, THORNTON-DIBB S, KONGO V, WILES L, BLIGHT J, STUART-HILL SI, VERSFELD D, TOMLINSON K (2009b) *Methods and guidelines for the licensing of SFRAs with particular reference to low flows*. WRC Report No. 1428/1/09, Water Research Commission, Pretoria, South Africa.

KUNZ R, MABHAUDHI T (2023) *Volume 2: Climate change atlas for rainfed production of selected underutilised crops*. WRC Report No. 2717/2/23, Water Research Commission, Pretoria, South Africa. 145 pp.

KUNZ R, MASANGANISE J, REDDY K, MABHAUDHI T, LEMBEDE L, NAIKEN V, FERRER S (2020) *Water use and yield of soybean and grain sorghum for biofuel production*. WRC Report No. 2491/1/20, Water Research Commission, Pretoria, South Africa. 361 pp.

KUNZ R, DAVIS NS, THORNTON-DIBB SLC, STEYN JM, DU TOIT ES, JEWITT GPW (2015) Assessment of biofuel feedstock production in South Africa: Atlas of water use and yield of biofuel crops in suitable growing areas (Volume 3). WRC Report No. 652/15, Water Research Commission, Pretoria, South Africa.

KUNZ R, REDDY K, MTHEMBU T, LAKE S, CHIMONYO V, MABHAUDHI T (2024) *Crop and nutritional water productivity of sweet potato and taro*. WRC Report No. 3124/1/24, Water Research Commission, Pretoria, South Africa.

LAKE S (2024) *A novel approach to mapping areas suitable for rainfed production of bambara nut and cowpea*. MSc dissertation, Centre for Water Resources Research, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg.

LEONI M, MUSIO S, CROCI M, TANG K, MAGAGNINI GM, THOUMINOT C, MÜSSIG J, AMADUCCI S (2022) The effect of agronomic management of hemp (*Cannabis sativa* L.) on stem processing and fibre quality. Industrial Crops & Products **188** 115520.

LINDER ER, YOUNG S, LI X, INOA SH, SUCHOFF DH (2022) The effect of transplant date and plant spacing on biomass production for floral hemp (*Cannabis sativa L.*). Agronomy **12 (8)** 1856.

LISSON SN, MENDHAM NJ, CARBERRY PS (2000) Development of a hemp (*Cannabis sativa* L.) simulation model. 4. Model description and validation. Australian Journal of Experimental Agriculture **40 (3)** 425-432.

LYNCH S (2004) *Development of a raster database of annual, monthly and daily rainfall for southern Africa*. WRC Report No. 1156/1/04, Water Research Commission, Pretoria, South Africa.

MABHAUDHI T (2012) Drought tolerance and water-use of selected South African landraces of taro (Colocasia esculenta L. Schott) and bambara groundnut (Vigna subterranea L. Verdc). Unpublished PhD thesis. Crop Science discipline, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, RSA.

MCMASTER GS, WILHELM WW (1997) Growing degree-days: one equation, two interpretations. Agricultural and Forestry Meteorology **87 (4)** 2915-300.

MEIER CH, MEDIAVILLA V (1998) Factors influencing the yield and the quality of hemp (*Cannabis sativa* L.) essential oil. Journal of the International Hemp Association **5 (1)** 16-20.

MORGAN W, SINGH J, KESHEIMER K, DAVIS J, SANZ-SAEZ A (2024) Severe drought significantly reduces floral hemp (*Cannabis sativa* L.) yield and cannabinoid content but moderate drought does not. Environmental and Experimental Botany **219** 105649.

PEREIRA LS, PAREDES P, HUNSAKER DJ, LÓPEZ-URREA R, MOHAMMADI SHAD Z (2021) Standard single and basal crop coefficients for field crops. Updates and advances to the FAO56 crop water requirements method. Agricultural Water Management **243** 106466.

RAES D, FERERES E, GARCÍA VILA M, CURNEL Y, KNODEN D, ÇELIK SK, UCAR Y, TÜRK M, WELLENS J (2023) Simulation of alfalfa yield with AquaCrop. Agricultural Water Management **284** 108341.

RAES D, STEDUTO P, HSIAO TC, FERERES E (2009) AquaCrop - The FAO crop model to simulate yield response to water: II. Main algorithms and software description. Agronomy Journal **101 (3)** 4385-447.

RAES D, STEDUTO P, HSIAO TC, FERERES E (2018) *AquaCrop Version 6.0 - 6.1 reference manual*. Land and Water Division, Food and Agricultural Organisation (FAO) of the United Nations, Rome, Italy.

RAES D, STEDUTO P, HSIAO TC, FERERES E (2022) AquaCrop Version 7.0 reference manual. Land and Water Division, Food and Agricultural Organisation (FAO) of the United Nations, Rome, Italy.

SEBASTIAN J, DONG X, TROSTLE C, PHAM H, JOSHI MV, JESSUP RW, BUROW MD, PROVIN TL (2023) Hemp agronomy: current advances, questions, challenges, and opportunities. Agronomy **13** 475.

SCHULZE RE (1995) *Hydrology and agrohydrology: A text to accompany the ACRU 3.00 agrohydrological modelling system*. WRC Report No. TT 69/9/95, Water Research Commission, Pretoria, South Africa.

SCHULZE RE (2011) Methods 3: Modelling impacts of climate change on the hydrological system: Model requirements, selection of the ACRU model, its attributes and computations of major state variables and outputs. In: *Methodological approaches to assessing eco-hydrological responses to climate change in South Africa,* SCHULZE RE, HEWITSON BC, BARICHIEVY KR, TADROSS M, KUNZ RP, HORAN MJC, LUMSDEN TG, Chapter 8, 75-88. WRC Report No. 1562/1/10, Water Research Commission, Pretoria, South Africa.

SCHULZE R (2023) A national assessment of potential climate change impacts on the hydrological yield of different hydro-climatic zones of South Africa: report 3 - South African and international verification studies of the ACRU daily time-step model across a range of processes, applications and spatial scales. WRC Report No. 2833/3/22, Water Research Commission, Pretoria, South Africa.

SCHULZE RE, MAHARAJ M (2004) *Development of a database of gridded daily temperatures for Southern Africa*. WRC Report No. 1156/2/04, Water Research Commission, Pretoria, South Africa.

SCHULZE RE, SCHÜTTE S (2023) Mapping SCS hydrological soil groups over South Africa at terrain unit spatial resolution. Journal of the South African Institution for Civil Engineering **65 (4)** 2-9.

SCHULZE RE, HORAN MJC, KUNZ RP, LUMSDEN TG, KNOESEN DM (2011) Methods 2: Development of the southern African quinary catchments database. In: *Methodological approaches to assessing eco-hydrological responses to climate change in South Africa*, SCHULZE RE, HEWITSON BC, BARICHIEVY KR, TADROSS M, KUNZ RP, HORAN MJC, LUMSDEN TG, Chapter 7, 63-74. WRC Report No. 1562/1/10, Water Research Commission, Pretoria, South Africa.

SCHÜTTE S, SCHULZE R, CLARK D (2023) A national assessment of potential climate change impacts on the hydrological yield of different hydro-climatic zones of South Africa: report 1 - methodology and results. WRC Report No. 2833/1/22, Water Research Commission, Pretoria, South Africa.

SCOTT DF, SMITH RE (1997) Preliminary empirical models to predict reductions in annual and low flows resulting from afforestation. Water SA **23 (2)** 135-140.

SMITHERS JC, SCHULZE RE (1995) *ACRU agrohydrological modelling system: User manual Version 3.00*. WRC Report No. TT 70/95, Water Research Commission, Pretoria, South Africa.

STEDUTO P, HSIAO TC, FERERES E, RAES D (2012) *Crop yield response to water*. FAO Irrigation and Drainage Paper No. 66, Rome, Italy.

STEDUTO P, HSIAO TC, RAES D, FERERES E (2009) AquaCrop - the FAO crop model to simulate yield response to water: I. Concepts and underlying principles. Agronomy Journal **101 (3)** 4265-437.

SAXTON KE, SAWLS WJ (2006) Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Science Society of America Journal **70 (5)** 1569-1578.

STRUIK PC, AMADUCCI S, BULLARD, MJ, STUTTERHEIM NC, VENTURI G, CROMACK HTH (2000) Agronomy of fibre hemp (*Cannabis sativa L*.) in Europe. Industrial Crops and Products **11 (2-3)** 107-118.

TANG K, FRACASSO A, STRUIK PC, YIN X, AMADUCCI S (2018) Water- and nitrogen-use efficiencies of hemp (*Cannabis sativa* L.) based on whole-canopy measurements and modelling. Frontiers in Plant Science **9**.

TANG K, STRUIK PC, YIN X, CALZOLARI D, MUSIO S, THOUMINOT C, BJELKOVÁ M, STRAMKALE V, MAGAGNINI G, AMADUCCI S (2017) A comprehensive study of planting density and nitrogen fertilization effect on dual-purpose hemp (*Cannabis sativa L.*) cultivation. Industrial Crops and Products **107** 427-438.

TANG K, STRUIK PC, YIN X, THOUMINOT C, BJELKOVÁ M, STRAMKALE V, AMADUCCI S (2016) Comparing hemp (*Cannabis sativa* L.) cultivars for dual-purpose production under contrasting environments. Industrial Crops and Products **87** 33-44.

TOUCHER ML, RAMJEAWON M, MCNAMARA MA, ROUGET M, BULCOCK H, KUNZ RP, MOONSAMY J, MENGISTU M, NAIDOO T, VATHER T (2020) Resetting the baseline land cover against which stream flow reduction activities and the hydrological impacts of land use change are assessed. WRC Project No. K5/2437, Water Research Commission, Pretoria, South Africa.

VON HOYNINGEN-HUENE J (1983) Die Interzeption des Niederschlages in landwirtschaftlichen Pflanzenbeständen. Deutscher Verband für Wasserwirtschaft und Kulturbau. Schriften **57** 1-66. Verlag Paul Parey, Hamburg Germany.

WARBURTON ML, SCHULZE RE and JEWITT GPW (2010) Confirmation of ACRU model results for applications in land use and climate change studies. Hydrology and Earth System Sciences **14** 2399-2414.

WELLENS J, RAES D, FERERES E, DIELS J, COPPYE C, ADIELE JG, EZUI KSG, BECERRA, LA, GOMEZ SELVARAJ M, DERCON G, HENG LK (2022) Calibration and validation of the FAO AquaCrop water productivity model for cassava (Manihot esculenta Crantz). Agricultural Water Management **263** 107491.

WIMALASIRI EM (2023) Personal communication. Senior Lecturer in the Faculty of Agricultural Sciences, Sabaragamuwa University, Belihuloya, Balangoda, Sri Lanka, 25 July 2023.

WIMALASIRI EM, JAHANSHIRI E, CHIMONYO V, AZAM-ALI SN, GREGORY PJ (2021a) Crop model ideotyping for agricultural diversification. MethodsX **8** 101420.

WIMALASIRI EM, JAHANSHIRI E, CHIMONYO VGP, KURUPPUARACHCHI N, SUHAIRI TASTM, AZAM-ALI SN, GREGORY PJ (2021b) A framework for the development of hemp (*Cannabis sativa* L.) as a crop for the future in tropical environments. Industrial Crops & Products **172** 113999.

WIMALASIRI EM, JAHANSHIRI E, SYAHERAH TA, KURUPPUARACHCHI N, CHIMONYO VGP, AZAM-ALI SN, GREGORY PJ (2022) Datasets for the development of hemp (*Cannabis sativa* L.) as a crop for the future in tropical environments (Malaysia). Data in Brief **40** 107807.

WISE K, BAZIOTOPOULOS E, ZHANG C, LEAMING M, SHEN L, SELBY-PHAM J (2023) Comparative study of water requirements and water footprints of fibre crops hemp (*Cannabis sativa*) and cotton (*Gossypium hirsutum* L.). Journal of Agrometeorology **25 (3)** 392-396.

WONG CL, LIEW J, YUSOP Z, ISMAIL T, VENNEKER R, UHLENBROOK S (2016) rainfall characteristics and regionalization in peninsular Malaysia based on a high resolution gridded data set. Water **8** 500.

ŽYDELIS R, HERBST M, WEIHERMÜLLER L, RUZGAS R, VOLUNGEVIČIUS J, BARČAUSKAITĖ K, TILVIKIENĖ V (2022) Yield potential and factor influencing yield gap in industrial hemp cultivation under nemoral climate conditions. European Journal of Agronomy **139** 126576.

CHAPTER 7 PRELIMINARY SOCIO-ECONOMIC ANALYSIS AND STAKEHOLDER ENGAGEMENT

Authors: Jamie Botha and Sukhmani Mantel

7.1 Introduction

Globally, cannabis production is on the rise as governments decriminalize and legalize its cultivation, processing, and trade. In South Africa, cannabis use has been decriminalized, and export sales are permitted, recognizing its economic potential. However, domestic trade remains restricted, and large-scale cultivation for profit is prohibited within national borders.

Mpondoland in the Eastern Cape has historically been the heart of South Africa's cannabis cultivation. Legacy growers have not benefited from recent legal changes despite their expertise and cultural heritage. These growers now face greater challenges in achieving profitability and accessing markets.

This analysis aims to capture the perspectives of cannabis farmers in Mpondoland and identify the barriers preventing them from achieving economic success and integration into the Value Chain (VC) of cannabis production. Framing the industry as part of the VC highlights opportunities for policies that foster local linkages, enhance production capabilities, and develop branding strategies to maximise value retention within South Africa.

7.2 Cannabis cultivation and rural livelihoods in South Africa

The new Cannabis industry is poorly understood because for the better part of the 20th century, it was illegal and there is little to no research on it. One of the key points of research is its water use, this is especially important here in South Africa since it is a water-scarce country (Hellberg, 2020). The past recreational use, criminalisation and public perception of Cannabis comprise a non-trivial component of any risk assessment of a potential VC.

The market for certified *C. sativa* products has been developing over many decades. The history of Cannabis production and its regulation is well documented, with the general emphasis having been to separate the high tetrahydrocannabinol (THC) and low-THC varieties, and to certify the low-THC varieties for use in hemp and cannabidiol (CBD) oil production (Bouloc, 2013). The existence of a VC for low THC products is firmly established in the commercial hemp and CBD oil industry. Other premium products that are being developed from *C. sativa* and that have the potential to create VCs for commercial sale include certified seed production, high-value CBD oil, and high-value THC products for pharmacological and medicinal use.

The growing demand for high-value agriculture commodities is important in developing countries, but producers need to understand and comply with the specifications of the value chain to reduce risks that the industry is facing (Spies, 2011). All farmers at a primary production level are exposed to many technical risks including non-compliance with value-chain certifications, access to capital, market variability, financial risk and environmental compliance (Jaffee et al., 2010).

Managing risks that farmers face in any value chain needs to be assessed (Spies, 2011). Roduner (2007: p.4) defines three useful terms that we use in this report:

- **Value chain actors:** The chain of actors who directly deal with the products, i.e. produce, process, trade and own them.
- **Value chain supporters:** The services provided by various actors who never directly deal with the product, but whose services add value to the product.
- **Value chain influencers:** The regulatory framework, policies, infrastructures, etc. (at the local, national and international level).

Chart 1: The value chain system (adapted from USAID, 2006)

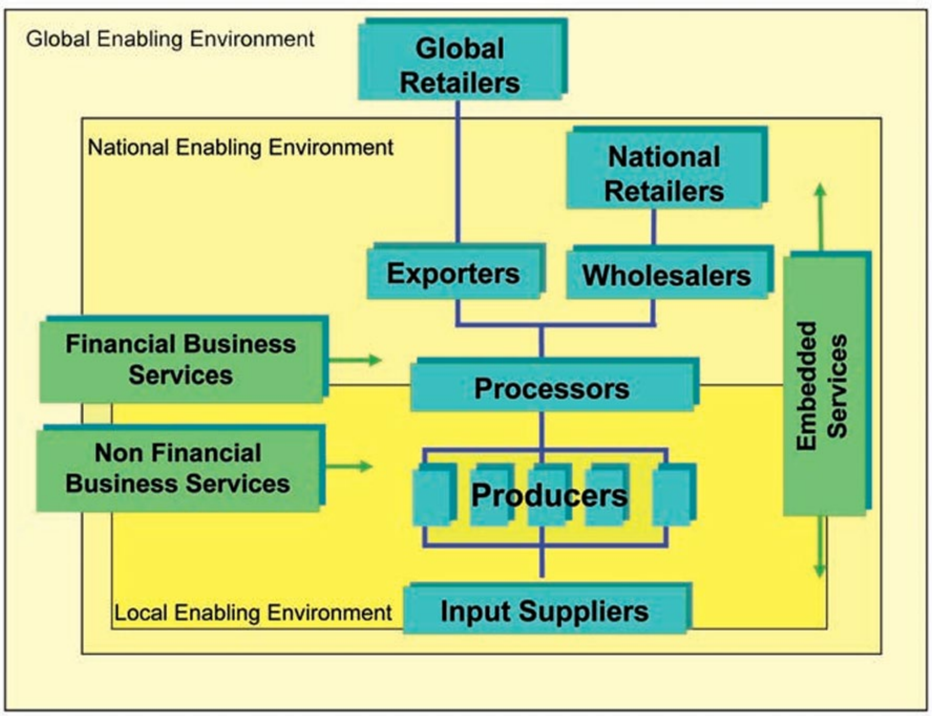

Figure 7-1 Value chain system (Source: Roduner, 2007) for analysing potentials and bottlenecks

Roduner (2007) states that these are three levels within a value chain network (Figure 7-1) that can help uncover potentials and bottlenecks, and highlight dynamic interactions. Sturgeon (2008) notes that the rules set for any institution (in its broadest concept) is influenced to varying degrees by the beliefs, values, meanings and priorities of the societies which create, fund and staff them. It is important to build the history of cultural and religious practices surrounding Cannabis, as well as the criminalisation of *C. sativa* into the risk assessment and VC.

In South Africa, farmers in poor rural areas struggle to participate in commercial markets (Khapayi and Cellier, 2016; Louw and Jordaan, 2019). The planned de-regulation of *C. sativa* production affords these small-scale growers an important opportunity. Still, understanding the risks associated with value chains is crucial to advising the type of intervention supported by policy, and the target premium markets that the value chains should focus on.

Although most value-chain research in South Africa has been based on fresh produce (Louw and Jordaan, 2019), meat (OABS Development Pty Ltd, 2018) and fibre (mohair and wool) industries (Craig, 2008), there has also been valuable work done on assessing the barriers to entry by small-scale farmers and the need for a clear understanding of the importance of compliance to the certification processes in these markets.

Understanding value chains has recently assumed importance in livestock marketing (Lipson Feder et al., 2021; Katz and Boland, 2000). In South Africa livestock production is one of the most critical farming practices, and Woolworth's product specifications and standards have existed for the High-Value Beef (HVB) project, a collaboration between DAFF (now DFFE), Agricultural Research Council (ARC), National Agricultural Marketing Council, Cavalier Meats, Cradock Abattoir and the Australian Centre for International Agricultural Research (ACIAR). This project has demonstrated that training producers as to the necessity for compliance, the establishment of clear operating procedures and convincing them of the added value that a premium product delivers, is crucial to VC success. In addition, it is also vital to identify non-compliant producers early to avoid their withdrawal from the project. Smallholder farmers are particularly vulnerable to failure when products are out of market specification and do not meet consumer needs.

The participants in any value chain need to be informed about the risk of non-compliance to certification at an early stage in participation, since product that is out of specification or non-compliant is penalised by the processor through pricing discounts. When non-compliance occurs, the prices have to be relocated to lower markets or will cost more in processing to fit them into a specified market. However, products that are out of specification can contribute to an economic loss (Slack-Smith et al., 2009).

The establishment of a *C. sativa* VC can lead to improved production practices, including but not limited to improved natural resource management practices, better soil conservation measures, and confirmed adherence to pesticide and herbicide regulations. The value chain can include adherence to several non-production criteria such as inclusion of small-scale producers, poverty alleviation, job creation and inclusion of labour in share-farming options.

Production-related decision-support systems are emerging in Europe, e.g., Amaducci et al. (2012), but are in the early stages, and need to be developed with semi-arid and arid systems in the global south. Yield varies considerably between cultivars and within different environments, and more research into metabolite regulation and expression is needed, particularly those connected with responses to stress (Schluttenhofer & Yuan, 2017), life history stage and fitness (Andre et al., 2016).

New market opportunities will drive a need for more plant breeding and agronomic research (Gray et al., 2016). The majority of production will likely come from a few cultivars. However, small producers may hybridize new varieties, or combine varieties into their products, resulting in marketable and desirable effects and flavours as has happened with coffee, craft beer and wine (Gray et al., 2016).

7.2.1 Modern-day perception of Cannabis

In America, the negative view of Cannabis started in the late 19th century to early 20th century when it was viewed as a drug used by mostly minorities, such as Latinos and African Americans, and was associated with increased crime rate (Galliher and Cross, 1982; Warf, 2014). This culminated in the enactment of laws which prohibited its use in many countries across the globe (Sloman, 1998; Warf, 2014).

In 1938, the Marijuana Tax Act was passed (Cherney and Small, 2016). This severely limited the use of hemp, requiring growers to seek permission from the U.S. Department of Agriculture (USDA) to grow hemp (Cherney and Small, 2016, Whitmer 2020). Its prohibition in the US was also fuelled by the cotton farmers who feared the competition from hemp production (Galliher and Cross, 1982; Baum, 1996). The Comprehensive Drug Abuse Prevention and Control Act of 1970 was passed. This legally separated Cannabis based on use but did not clear the way for production.

The recreational use of *C. sativa* saw an increase in the US during the 1960s when middle-class, university students and white Americans started using it. The Vietnam War played a role in the increased recreational use of Cannabis; anti-war activists such as “Hippies” (a counterculture that formed in the USA and was opposed to war) regularly used *C. sativa* for recreational use (Warf, 2014).

The growing number of *Cannabis* users led to the decriminalisation of the plant in many states and countries. In some states like Colorado and countries like Canada, recreational use of *C. sativa* has been legalized and countries like South Africa have permitted the private use of *C. sativa* thus opening up a whole new industry.

The role of legislation and VC in determining the income from trading cannabis products in South Africa has not been clear (Manu et al., 2021). A case study from the Eastern Cape illustrated that the monetary value of cannabis to rural livelihoods arises from an interplay of social/institutional factors including land tenure, risk appetite and legislation on top of ecological factors such as soil quality and water access (Kepe, 2003). The author elegantly highlighted the irony that the illegality of *Cannabis* contributes to higher derived income (Kepe, 2003). See Chapter 2 of this deliverable for more recent work in the Eastern Cape.

7.2.2 Cannabis cultivation and rural livelihoods

Although hemp is well adapted to the temperate climatic zone and will grow under varied environmental conditions, it grows best with warm growing conditions, an extended frost-free season, highly productive agricultural soils, and abundant moisture throughout the growing season. Oil production requires a warmer climate, and the growing season needs to be five to six weeks longer than the 120 days required for fibre production (Ehrensing, 1998).

When grown under proper conditions, Cannabis is very competitive with weeds, and herbicides are generally not required. Although several insect pests and diseases have been reported on hemp, significant crop losses from pests are not common. Production costs are quite similar to corn's (Ehrensing, 1998).

Cannabis can be cultivated for biomass and fibre for non-food industrial uses such as energy, construction and automotive markets, or for seeds which are components of food, animal feeds and medicinal products. Oil, collectively called “essential oils” or cannabinoids, can be extracted from the seeds or buds of high or low THC content varieties.

Cannabis can be grown from seeds or cuttings, although there is a trend of an increasing number of Cannabis growers moving from using cuttings from female “mother plants” to seeds in the last few years (Lipson Feder et al., 2021). Depending on the products the seeds can be feminised, but typically in these cases, 5–10% of the plants will be male.

7.2.3 South African traditional or legacy farmers

It is estimated that there are more than 900,000 legacy growers in the Eastern Cape and KwaZulu Natal provinces of South Africa (Department of Agriculture Land Reform and Rural Development, 2021). The 2023 report by the Institute for Economic Justice (IEJ) discusses the National Cannabis Masterplan Process (NCMP), an initiative focused on fostering fair and inclusive economic growth, job creation through skill development, and environmental sustainability (Bowman and Lehmann-Grube, 2023). The report's primary objective is to integrate legacy or traditional growers into the formal supply chain. The IEJ report emphasizes several challenges that require attention, including issues related to global competition and regulatory barriers, competition leading to downward pricing pressures, and adherence to social principles such as promoting decent work and ensuring environmental sustainability to safeguard reputation. Additionally, the report underscores the importance of social equity for traditional growers and suggests leveraging domestic demand to support overall industry growth.

Literature (grey and published) suggests some practices that need to be considered for supporting small-scale farmers once Cannabis has been commercially legalized for cultivation and trade, including:

- The Bowman and Lehmann-Grube (2023) report notes that landrace varieties grown by these legacy farmers are indigenous knowledge that is under threat from bio-piracy and breeding with other varieties and that these issues are not appropriately included in the National Cannabis Masterplan Process (NCMP). One suggested solution is that these growers focus on niche products for legal adult use and regulations support the creation of an inclusive cannabis economy.
- Manu et al.'s (2021) in-depth interviews with illicit marijuana growers in the Eastern Cape raised both positive and negative aspects of legalization. Although the freedom to grow and expand cultivation and potential unionization were considered positives, a fall in price and increased supply and competition with white commercial farmers and other small-scale growers, resulting in rural communities losing out on cannabis as a source of livelihood were also raised. The negative impacts could result in greater rural-urban migration.
- Fair Trade practices and value chain need to be evaluated to promote the products generated by legacy farmers. Manu et al. (2021) recommended a license or certification requirement for growing (e.g. in California). However, the cost should be low to allow small-scale farmers to easily afford it. The IEJ report on Inclusive Development in the South African Cannabis industry notes that >70 licenses for export-quality medical cannabis have been awarded (Bowman and Lehmann-Grube, 2023).
- A Ludolph (2022) article on the Food for Mzansi website records a suggestion by a former Cannabis farmer from Mpondoland (Grek Zweni) who recommended that the creation of a hub by the government, similar to hubs for other crops would assist farmers who can bring their harvest to the hub for processing and marketing. Illicit growers in the Easter Cape interviewed by Manu et al. (2021) also noted that legalisation could raise the possibility of creating a union which would increase their bargaining power.

Two theses on Mpondoland farmers provide a detailed analysis of the socio-economic landscape of contribution of Cannabis to livelihoods of small-scale farmers in Eastern Cape, South Africa. These theses were published recently (2021 and 2023), and they are summarised below.

7.2.4 Højgaard thesis: Cannabis production and rural livelihoods

Ida Højgaard's (2021) thesis titled 'Illicit cannabis production and rural livelihoods in Mpondoland, South Africa'. is a detailed study of contribution of Cannabis to rural livelihoods in the Eastern Cape. She notes that the Eastern Cape hosts a lot of biodiversity and the climate is conducive to rainfed agriculture, although the poor soil is limiting for farmers to conduct extensive farming. Cannabis, however, can survive and flourish in harsh environments. Eastern Cape's hilly and gorged area has also limited access by law enforcement and thus, Mpondoland has in the past been the main Cannabis producer in south Africa, as noted by Kepe (2003) and Duvall (2019, 2023).

Ida conducted fieldwork in two inland and two coastal communities, which included observations related to cannabis farming, household surveys, and interviews. Ida's thesis addressed two research questions related to rural livelihoods:

- What is the contribution of cannabis to rural income in the case study communities, and what are the characteristics of people and households who depend most on this source of income?
- Other than income, how is cannabis farming impacting people's livelihoods compared to other occupations?

Ida's findings indicated that Cannabis could contribute up to half the household income in some communities and it serves as a 'safety net' for many such as during COVID-19 pandemic. Many farmers are sceptical of the legislation due to the historical negative experience with law enforcement agencies. She noted that the lack of diversification in income, with dependence on cannabis and government social grants, is important for decision-makers to consider when drafting legislation. In terms of future of cannabis for rural communities, there are various concerns such as access to markets, competition with technologically advanced businesses, and prices for the crop.

7.2.5 Grooten thesis: Harvesting hope

The thesis by Tijmen Simon Grooten (2023) is titled 'Harvesting Hope: Exploring the Untapped Potential of Smallholder Cannabis Farming in South Africa'. Grooten conducted open-ended interviews, household survey, and participant observations. Here are some key relevant points from Grooten's work highlighted in the thesis and the Policy Brief Addendum to the thesis:

- Current cannabis licensing systems favours corporations or large-scale commercial farmers over traditional small-scale farmers (e.g. through free market competition), highlighting the need for inclusive policies to address this inequality. Traditional farmers face challenges such as shifting demand toward high-grade strains, which threatens their economic viability and contributes to declining living standards, food insecurity, and socio-economic stress.
- Although there is considerable economic potential in landrace cultivation by smallholders in Mpondoland (or the Dagga Belt region), there are currently no legal pathways to capitalise on this opportunity. Rural legacy farmers can thrive economically only with legal reforms aimed at empowering them. Unequal economic participation in the cannabis sector

risks loss of traditional cultivation practices and indigenous genetics, making urgent protective measures essential for their preservation.

- To address economic and political inequality in the cannabis industry, policy reforms must prioritize resource-poor legacy farmers. Implementing the policy principles established in the Phakisa Action Lab is crucial to prevent further poverty and unlock economic potential. Instead of favouring corporate interests, new policies should create preferential conditions for traditional cannabis growers, offering them reparations and economic opportunities as a matter of social justice.

Grooten notes the limited knowledge of traditional practices of smallholder cannabis farmers, which are important to investigate and record in order to ensure that the legal framework *(value chain influencer)* aligns with those. This is the justification for the work he conducted. Grooten (2023) came up with various policy recommendations, including:

- The government needs to draft comprehensive legislation that legalises the cultivation, possession, trade by smallholder farmers. Additionally, partnerships with licensed companies can be promoted along with setting a minimum price. The legislation needs to consider ways to protect smallholder farmers, and implement market measures to support rural development.
- For effective implementation, government staff need to be educated on cannabis value chains, quantify Mpondoland production in order to market it appropriately, and ancestral farmers need to be engaged by policymakers for targeted support and viable business protection.
- To promote farmers' cooperatives, the government should provide clear guidelines for organizing and registering farmer groups. Local extension officers can facilitate group formation, which would serve as primary government contact points for cooperative and individual licensing
- To prevent illegal activity, cannabis farmers need reliable markets. A pilot project in Mpondoland should integrate product development and market exploration, involving research institutions like CSIR and partnerships with licensed construction firms like Afrimat. To note, hempcrete masonry and other hemp products are being made commercially in Cape Town by Afrimat (https://www.afrimathemp.co.za/).
- The study recommended exploring niche cash crops and cannabis tourism, with improved infrastructure in Mpondoland to boost economic opportunities.

7.3 Stakeholder engagement: interviews and focus groups

7.3.1 Methodology

The research employed Action Research, an iterative, collaborative process that generates practical solutions while empowering participants. As Julienne Meyer (2000) explains, this approach involves working <u>with</u> and <u>for</u> people rather than researching *on* them. Data were gathered during a focus group discussion and through questionnaires administered at a Cannabis Knowledge Workshop hosted by the Township Cannabis Incubator in Mthatha, Eastern Cape (led by Dr Galada). See Appendix B for the ethical clearance certificate and questionnaire.

Steps were taken to address conflicting responses in the questionnaire data. Conflicting responses were resolved by prioritizing initial questionnaire data: participants 15-17 reported less than one year of cannabis cultivation (Question 1), Participant 12's response about implementing sustainable practices was revised to "Yes" (Question 12), Participant 10's regulatory compliance challenges were clarified (Question 14), and Participant 13's views on the future of small-scale cannabis farming were refined (Question 19).

7.3.2 Descriptive and comparative analysis: Data overview

Data collection involved:

- A focus group discussion with 20 participants (Figure 7-2), was led by Mr Botha and his research assistant, Ms Claire Cattaneo.
- A questionnaire completed by participants after a workshop presentation.
- Mr Botha recorded his personal observations before and after the workshop.

Participants represented diverse groups, including local government officials from the Oliver Tambo District Municipality (OTDM), small and medium enterprises linked to agriculture or cannabis, students from Walter Sisulu University and ILHAM, and a few aspiring cannabis cultivators. Ages ranged from 22 to 62, and participants were predominantly people of colour.

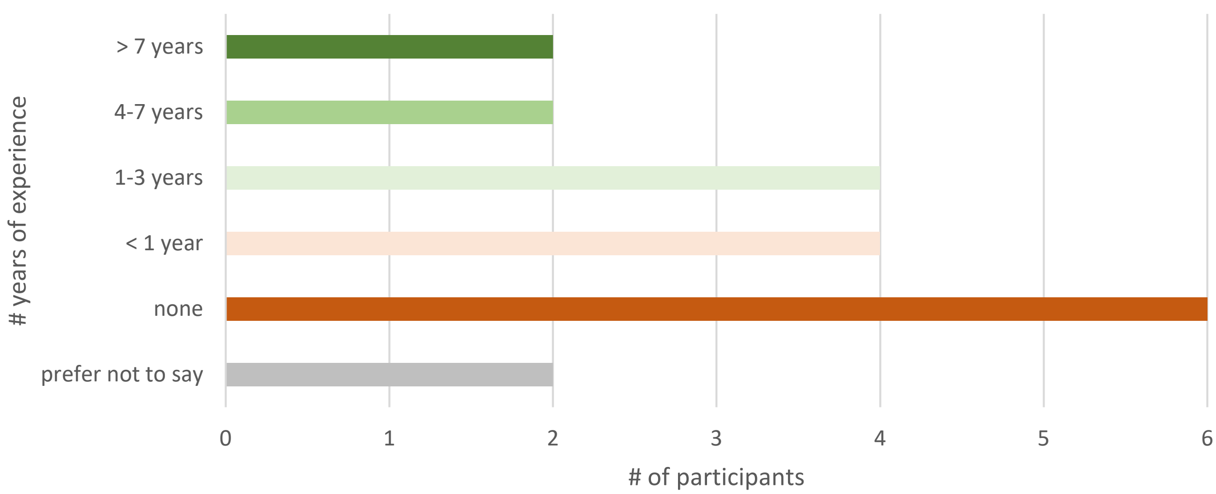

Figure 7-2 Number of participants by years of experience in Cannabis cultivation who were involved in the focus group discussion.

7.4 Results and discussion

7.4.1 Stakeholder analysis: stakeholder landscape

The stakeholder landscape surrounding legacy cannabis farming in Mpondoland is shaped by a range of actors with varying roles, interests, and levels of influence.

- **Legacy Farmers**: Traditional cultivators marginalized in the current regulatory and market environment.
- **Local Government (OTDM)**: Policymakers prioritizing community employment and economic transformation.
- **Academic Institutions**: Partners for research and skills development (e.g., Walter Sisulu University, ILHAM).
- **Small and Medium Enterprises (SMEs)**: Emerging industry players seeking market entry.

At the centre of this landscape are the **legacy farmers**, who have been cultivating cannabis in traditional dryland conditions for generations. Despite their deep knowledge and experience, these farmers are increasingly marginalized in the current regulatory and market environment. The legalization of cannabis in South Africa has not been accompanied by sufficient support for these farmers, leaving them without access to formal markets, modern technologies, or adequate legal recognition. Their primary concerns revolve around achieving recognition for their traditional practices, securing access to sustainable markets, and navigating the challenges posed by an evolving legal landscape that does not fully accommodate their needs.

Local **government bodies**, such as the **O.R. Tambo District Municipality (OTDM)**, play a key role in shaping the economic and social framework for cannabis farming in the region. Policymakers in this sphere focus on community employment and economic transformation, seeking to create opportunities that uplift local communities through the legal cannabis industry. Their interests align with fostering a more inclusive and equitable economic environment for both established and emerging farmers. However, challenges remain in aligning local government priorities with the complex realities of small-scale farming and the broader cannabis industry.

Academic institutions such as **Walter Sisulu University** and **ILHAM** (Institute for Land and Agricultural Management) serve as critical partners in research and skills development. These institutions provide essential support in the form of research, training, and capacity-building for local farmers. By partnering with farmers and other stakeholders, academic institutions aim to facilitate the transfer of knowledge and skills, helping to build a more sustainable cannabis farming sector. They are also involved in providing insights into market trends, legal frameworks, and agricultural innovations that could benefit local farmers, ensuring that the community is well-prepared for the evolving cannabis economy.

Emerging **small and medium enterprises (SMEs)** are also a growing presence in the cannabis sector. These new players seek market entry and are focused on establishing their businesses in the cannabis supply chain, ranging from cultivation to processing and distribution. SMEs are looking for opportunities to leverage the emerging legal framework, but they face challenges related to competition, market access, and regulatory compliance. While their success could lead to economic growth and job creation, SMEs must navigate a landscape that often favours larger, more established businesses with greater resources.

7.4.2 Engagement insights and key themes from the focus group discussion

The engagement insights from the focus group discussion and questionnaire responses revealed significant themes related to cannabis cultivation and commercialization in the Eastern Cape.

Participants in the focus group emphasized the synergistic effects of cannabinoids, particularly the interaction between CBD and THC, underscoring the complexity of cannabis as a medicinal and agricultural product. Sustainable cultivation practices emerged as a priority, with a focus on organic methods, proper water management, and the critical role of mycorrhizal fungi in enhancing nutrient uptake and plant resilience. Water management practices, such as providing plants with precise irrigation (e.g., four litres daily), were also discussed, along with a strong desire for community-led knowledge-sharing initiatives to improve local expertise in cannabis cultivation.

From the questionnaire, key themes included the challenges of market entry, with most participants perceiving access to markets as poor or very poor (Figure 7-3). Younger participants expressed a wider range of emotions regarding growth opportunities, contrasting with the more measured perspectives of older participants (Figure 7-4). Additionally, the importance of indigenous or local knowledge was a recurring theme, as many participants acknowledged its value in guiding their practices (Figure 7-5).

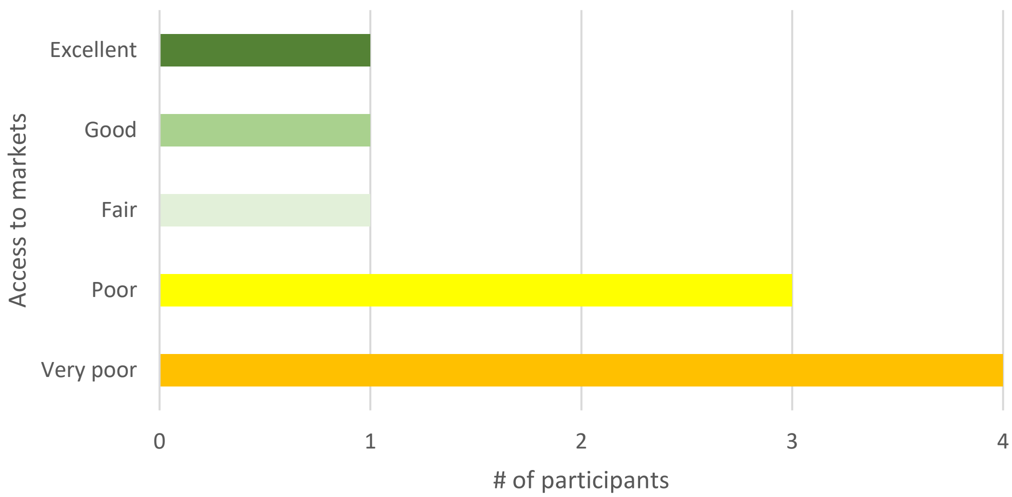

Figure 7-3 Of the 10 respondents who asked for technical training support (Q17), the majority had very poor or poor access to markets (Q15)

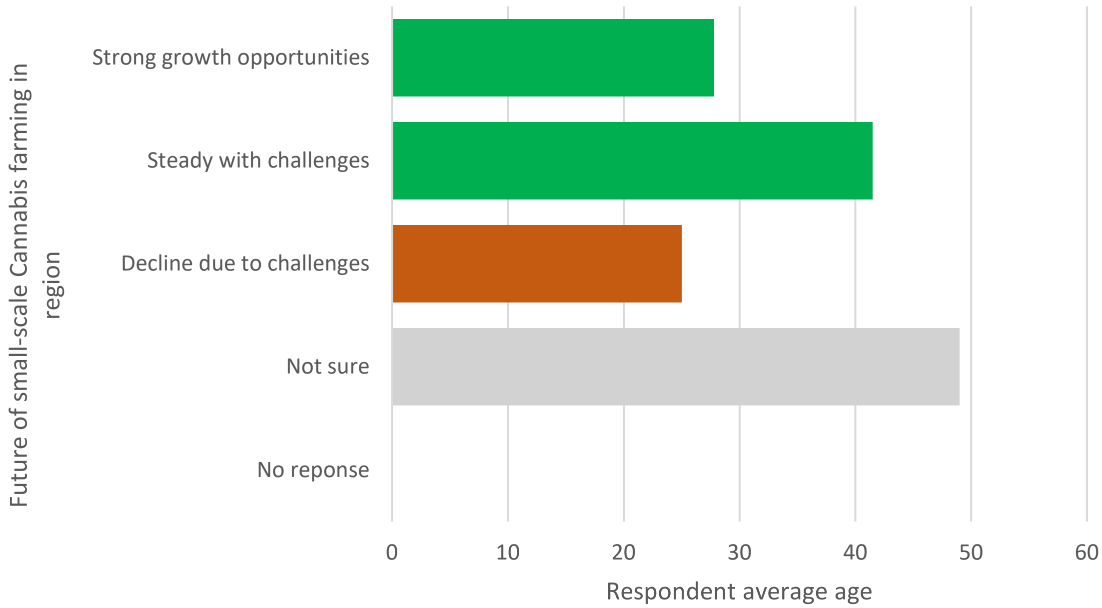

Figure 7-4 Correlation between perceptions of growth opportunities for small-scale Cannabis farmers in the region (Q19) and the average age of respondents

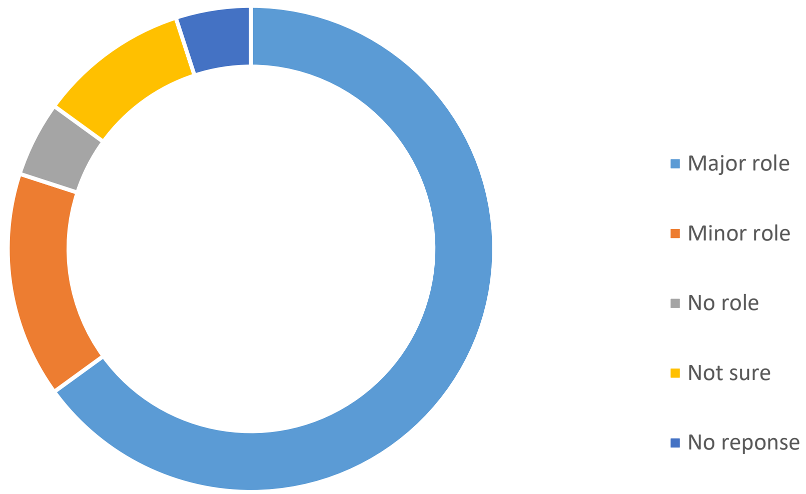

Figure 7-5 Respondents specified major role for indigenous or local knowledge in Cannabis cultivation (Q10)

The responses highlighted the diversity of the participants in terms of age, gender, experience, and knowledge of cannabis, as well as the complexity of cannabis production and commercialization within the region. These insights reflect the multifaceted challenges and opportunities faced by small-scale cannabis farmers in the Eastern Cape.

7.4.3 Relevance of global value chains for small-scale farmers

Research by Kaplinsky and Morris (2016) on Global Value Chains (GVC) underscores the importance of integrating local producers into additive VCs. For cannabis, this involves building local production linkages, upgrading technical capabilities, and fostering sustainable practices to maximize economic rents. Aligning with these strategies could significantly enhance the economic impact of cannabis cultivation in Mpondoland.

The research findings in both Ida Højgaard's Master's Thesis and the Socio-Economic Analysis align well with the principles outlined in Kaplinsky and Morris's (2016) research on global VCs. Their work highlights the importance of integrating local producers into value chains that add economic value at multiple levels. For cannabis cultivation in Mpondoland, these strategies resonate with the need to build local production linkages, upgrade technical capabilities, and foster sustainable practices.

Both documents emphasize the potential for cannabis to act as an economic driver if legacy farmers can be integrated into formal markets. This aligns with the GVC framework, which stresses that economic rents (profits retained locally) can be maximized by enhancing local production capabilities and ensuring small-scale producers have access to markets. The Socio-Economic Analysis explicitly ties this potential to policy interventions, such as cooperative farming models, local processing facilities, and simplified legal frameworks, which directly echo GVC strategies for local inclusion and value retention.

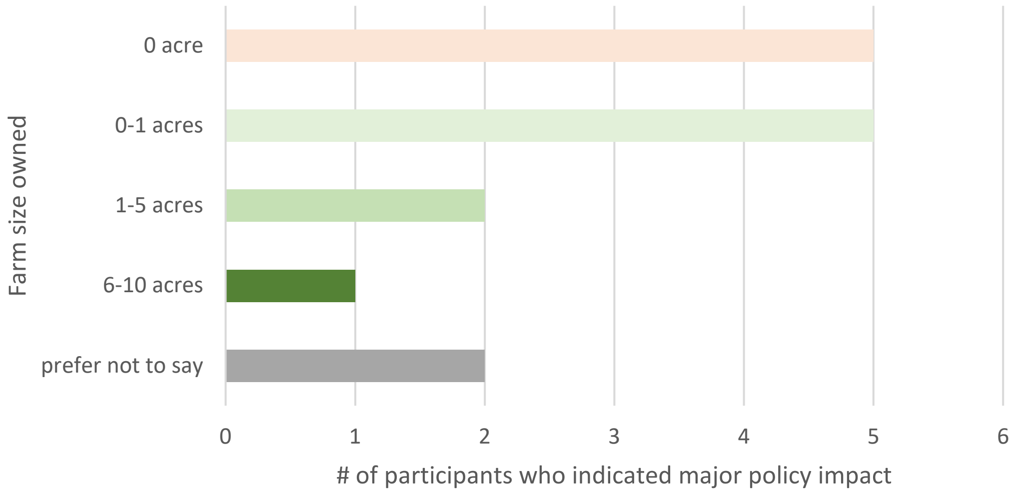

Figure 7-6 Fifteen of 20 individuals perceive a major negative impact of policy ambiguity (Q13). The figure shows the farm size of these individuals, with farmers owning 0-1 acres being dominant.

Sustainability is another critical intersection. Højgaard's Master's Thesis highlights traditional farming practices adapted to the region's environmental conditions, while the Socio-Economic Analysis stresses integrating these practices with modern techniques like precise irrigation and soil health management. Kaplinsky and Morris's emphasis on fostering sustainable practices as a component of GVC integration is reflected in these approaches, as sustainability ensures long-term viability and reduces ecological degradation, key for maintaining competitiveness in global markets.

Finally, the documents' calls for capacity building and technical training for farmers to navigate regulatory frameworks and adapt cultivation methods echo the GVC strategy of upgrading technical capabilities. By equipping farmers with skills and tools, they can move beyond raw material production to higher-value activities, such as processing and branding, which Kaplinsky and Morris identify as essential for maximizing local economic impact.

Figure 7-6 indicates that small-scale farmers (with less than 1-acre of land) perceive major negative impacts of policy ambiguity. Aligning the principles of inclusivity, sustainability, and capability upgrading emphasised by the VC framework with on-the-ground policies and practices could significantly enhance the region's economic outcomes from cannabis cultivation.

7.5 Summary and conclusion

Previous research has indicated that the socio-economic realities of cannabis cultivation in Mpondoland strongly support the GVC framework's emphasis on inclusivity, sustainability, and capability upgrading. Aligning these principles with on-the-ground policies and practices could significantly enhance the region's economic outcomes from cannabis cultivation.

Following is a summary of the engagement insights from the focus group.

Socio-Economic Indicators

- Income levels, employment opportunities, and education access varied significantly among participants, underscoring disparities in readiness to enter the formal cannabis market.

Barriers Identified

- Complex registration processes for growers.
- Limited access to domestic and international markets.
- Challenges in cultivar selection and adaptation to environmental conditions.

Opportunities Highlighted

- Organic cultivation methods.
- Adoption of sustainable practices, including water management and soil health improvement.
- Leveraging traditional knowledge while integrating modern techniques.

Comprehensive Findings

The analysis revealed:

- High potential for economic development through cannabis cultivation.
- Persistent barriers to market participation for legacy farmers.
- Strong community interest in adopting sustainable practices.
- The urgent need for supportive and integrated policy frameworks.

Implications

To unlock the potential of cannabis cultivation in Mpondoland:

- Economic empowerment programs must prioritize legacy farmers.
- Regulatory reform is essential for clear, accessible legal pathways.
- Sustainable, community-driven approaches should guide development.
- Academic and community knowledge must be integrated into industry practices.

Recent developments within the South African cannabis landscape such as agreements of intent between regional economic forums have provided some hope for possible growth in Mpondoland cannabis. It was recently reported that a memorandum of understanding has been signed between the Mpondoland Cannabis Belt Association and the Eastern Cape Rural Development Agency (ECRDA) (Algoa FM, 2024). This agreement seeks to enhance the commercial potential of Mpondoland's cannabis industry by prioritizing the preservation, safeguarding, and commercialization of indigenous cannabis landrace strains. The ECRDA also stated that its participation guarantees a sustainable, competitive, and community-oriented cannabis sector in Mpondoland.

7.6 References

ADLER JN and COLBERT JA (2013) Medicinal use of marijuana—polling results. N Engl J Med **368** (22) e30.

ALGOA FM (2024) High hopes for EC's cannabis industry, 29 November. URL: https://www.algoafm.co.za/domestic/high-hopes-for-ec-s-cannabis-industry.

AMADUCCI S, COLAUZZI M, BELLOCCHI G, COSENTINO SL, PAHKALA K, STOMPH TJ, WESTERHUIS W, ZATTA A and VENTURI G (2012) Evaluation of a phenological model for strategic decisions for hemp (*Cannabis sativa* L.) biomass production across European sites. Industrial Crops and Products Elsevier, **37** (1) 100–110.

ANDRE CM, HAUSMAN J-F and GUERRIERO G (2016) *Cannabis sativa*: the plant of the thousand and one molecules. Frontiers in plant science Frontiers Media SA, **7** 19.

BAUM D (1996) Smoke and mirrors: The war on drugs and the politics of failure. 396 pp.

BOULOC P (2013) Hemp: industrial production and uses. CABI.

BOWMAN A and LEHMANN-GRUBE K (2023) Inclusive development in the South African cannabis industry: Assessing the challenges. Institute for Economic Justice report, Johannesburg, South Africa. URL: https://www.iej.org.za/wp-content/uploads/2023/02/IEJ-CannabisReport-Feb2023.pdf

BRIDGEMAN MB and ABAZIA DT (2017) Medicinal cannabis: history, pharmacology, and implications for the acute care setting. Pharmacy and therapeutics MediMedia, USA, **42** (3) 180.

CHERNEY JH and SMALL E (2016) Industrial Hemp in North America: Production, Politics and Potential. Agronomy **6** (4). https://doi.org/10.3390/agronomy6040058.

COREY-BLOOM J, WOLFSON T, GAMST A, JIN S, MARCOTTE TD, BENTLEY H and GOUAUX B (2012) Smoked cannabis for spasticity in multiple sclerosis: a randomized, placebo-controlled trial. Cmaj Can Med Assoc, **184** (10) 1143–1150.

CRAIG KB (2008) Investigating teamwork competencies in the value chain of a selected wool brokerage logistics department. Doctoral dissertation, Nelson Mandela Metropolitan University.

DEPARTMENT OF AGRICULTURE LAND REFORM AND RURAL DEVELOPMENT (2021) Draft National Cannabis Master Plan for South Africa V. 5. URL: https://medicalcannabis.co.za/wp-content/uploads/2021/03/National-Cannabis-Master-Plan-for-South-Africa-Version-5.pdf

DUVALL CS (2019) *The African Roots of Marijuana*. Duke University Press, Durham and London. 344 pp.

DUVALL CS (2023) An African history of cannabis offers fascinating and heartbreaking insights - an expert explains. The Conversation. https://theconversation.com/an-african-history-of-cannabis-offers-fascinating-and-heartbreaking-insights-an-expert-explains-216281

EHRENSING DT (1998) Feasibility of Industrial Hemp Production in the United States. Oregon State University. Agricultural Experiment Station Bulletin 681 Oregon, 1–46.

GALLIHER JF and CROSS JR (1982) Symbolic severity in the land of easy virtue: Nevada's high marihuana penalty. Social Problems Oxford University Press Oxford, UK, **29** (4) 380–386.

GRAY DJ, BAKER H, CLANCY K, CLARKE RC, DECESARE K, FIKE J, GIBBS MJ, GROTENHERMEN F, KANE NC, KEEPERS KG, and co-authors (2016) Current and future needs and applications for Cannabis. Critical Reviews in Plant Sciences Taylor & Francis, **35** (5–6) 425–426. https://doi.org/10.1080/07352689.2017.1284529.

GROOTEN TS (2023) Harvesting hope: Exploring the untapped potential in South Africa. Wageningen University and Research.

HELLBERG S (2020) Scarcity as a means of governing: Challenging neoliberal hydromentality in the context of the South African drought. Environment and Planning E: Nature and Space **3** (1) 186–206. https://doi.org/10.1177/2514848619853551.

HØJGAARD I (2021) Illicit Cannabis Production and Rural Livelihoods in Mpondoland, South Africa. University of Copenhagen.

HUCHELMANN A, BOUTRY M and HACHEZ C (2017) Plant glandular trichomes: natural cell factories of high biotechnological interest. Plant Physiology **175** 6–22. https://doi.org/10.1104/pp.17.00727.

JAFFEE S, SIEGEL P and ANDREWS C (2010) Rapid Agricultural Supply Chain Risk Assessment: A Conceptual Framework. The World Bank.

JARABO R, FUENTE E, MONTE MC, SAVASTANO H, MUTJÉ P and NEGRO C (2012) Use of cellulose fibers from hemp core in fiber-cement production. Effect on flocculation, retention, drainage and product properties. Industrial Crops and Products **39** 89–96. URL: https://api.semanticscholar.org/CorpusID:96142979.

KAPLINSKY R and MORRIS M (2016) Thinning and thickening: productive sector policies in the era of global value chains. The European Journal of Development Research Springer, 28 625–645.

KATZ JP and BOLAND M (2000) A new value-added strategy for the US beef industry: the case of US Premium Beef Ltd. British Food Journal **5** (2) 99–109.

KEPE T (2003) *Cannabis sativa* and rural livelihoods in South Africa: Politics of cultivation, trade and value in Pondoland. Development Southern Africa **20** (5) 605–615. https://doi.org/10.1080/0376835032000149252.

KHAPAYI M and CELLIER PR (2016) Factors limiting and preventing emerging farmers to progress to commercial agricultural farming in the King William's Town area of the Eastern Cape Province, South Africa. South African Journal of Agricultural Extension **44** (1) 25–41.

LIPSON FEDER C, COHEN O, SHAPIRA A, KATZIR I, PEER R, GUBERMAN O, PROCACCIA S, BERMAN P, FLAISHMAN M and MEIRI D (2021) Fertilization following pollination predominantly decreases phytocannabinoids accumulation and alters the accumulation of terpenoids in Cannabis inflorescences. Frontiers in Plant Science **12** (November) 1–11. https://doi.org/10.3389/fpls.2021.753847.

LOUW A and JORDAAN D (2019) Supply chain risks and smallholder fresh produce farmers in the Gauteng province of South Africa. Southern African Business Review **20** 286–312. https://doi.org/10.25159/1998-8125/6051.

LUDOLPH N (2022) Cannabis: ‘Only the rich and connected are getting in’. Food For Mazansi. [Cannabis: 'Only the rich and connected are getting in' - Food For Mzansi].

MALIK A, FATEHI KS, MENON NN and CHATURVEDI P (2020) Review of medicinal use of cannabis derivatives and the societal impact of legalization. Indian Journal of Palliative Care United States, **26** (3) 369–380. https://doi.org/10.4103/IJPC.IJPC_19_20.

MANU E, DOUGLAS M, NTSABA MJ and TARKANG EE (2021) Perspectives of illicit marijuana growers and traders on commercial legalisation of marijuana in South Africa: considerations for policy formulation. Substance Abuse Treatment, Prevention, and Policy Substance Abuse Treatment, Prevention, and Policy, **16** (1) 54–66. https://doi.org/10.1186/s13011-021-00391-w.

MEYER J (2000) Using qualitative methods in health related action research. BMJ British Medical Journal Publishing Group, **320** (7228) 178–181.

NAFTALI T, SCHLEIDER LB-L, DOTAN I, LANSKY EP, BENJAMINOV FS and KONIKOFF FM (2013) Cannabis induces a clinical response in patients with Crohn’s disease: a prospective placebo-controlled study. Clinical Gastroenterology and Hepatology Elsevier, **11** (10) 1276–1280.

OABS DEVELOPMENT PTY LTD (2018) A Study on the Potential Product Development for the Commercialization and Value Add to Beef Products.

PANTHAPULAKKAL S and SAIN MM (2007) Studies on the water absorption properties of short hemp—Glass fiber hybrid polypropylene composites. Journal of Composite Materials **41** 1871–1883. URL: https://api.semanticscholar.org/CorpusID:137629846.

PISANTI S, BORSELLI C, OLIVIERO O, LAEZZA C, GAZZERRO P and BIFULCO M (2007) Antiangiogenic activity of the endocannabinoid anandamide: correlation to its tumor-suppressor efficacy. Journal of cellular physiology Wiley Online Library, **211** (2) 495–503.

RODUNER D (2007) Donor interventions in value chain development. Swiss Agency for Development and Cooperation SDC.

SCHLUTTENHOFER C and YUAN L (2017) Challenges towards revitalizing Hemp: A multifaceted crop. Trends in Plant Science Elsevier Ltd, **22** (11) 917–929. https://doi.org/10.1016/j.tplants.2017.08.004.

SLACK-SMITH A, GRIFFITH G and THOMPSON J (2009) The cost of non-compliance to beef market specifications. Australasian Agribusiness Review **17** 178–190.

SLOMAN L (1998) Reefer madness: a history of marijuana. Macmillan.

SPIES DC (2011) Analysis and Quantification of The South African Red Meat Value Chain. University of Free State.

STOCKINGS E, CAMPBELL G, HALL WD, NIELSEN S, ZAGIC D, RAHMAN R, MURNION B, FARRELL M, WEIER M and DEGENHARDT L (2018) Cannabis and cannabinoids for the treatment of people with chronic noncancer pain conditions: a systematic review and meta-analysis of controlled and observational studies. Pain LWW, **159** (10) 1932–1954.

STURGEON TJ (2008) From Commodity Chains to Value Chains: Interdisciplinary Theory Building in An Age of Globalization. Chapter 6. In: *Frontiers of Commodity Chain Research*. Stanford University Press. https://doi.org/https://doi.org/10.1515/9780804779760-008

TOTH JA, STACK GM, CALA AR, CARLSON CH, WILK RL, CRAWFORD JL, VIANDS DR, PHILIPPE G, SMART CD, ROSE JKC, and co-authors (2020) Development and validation of genetic markers for sex and cannabinoid chemotype in *Cannabis sativa* L. GCB Bioenergy **12** (3) 213–222. https://doi.org/10.1111/gcbb.12667.

WANG Q and XIONG YL (2019) Processing, Nutrition, and Functionality of Hempseed Protein: A Review. Comprehensive Reviews in Food Science and Food Safety **18** (4) 936–952. https://doi.org/10.1111/1541-4337.12450.

WARF B (2014) High points: an historical geography of cannabis. Geographical Review Taylor \& Francis, **104** (4) 414–438.

WELLHOFFER J (2020) The Effects of Light Spectra on the Growth and Development of Greenhouse CBD Hemp (May) 51.

WESTERHUIS W, VAN DELDEN SH, VAN DAM JEG, MARINHO JPP, STRUIK PC and STOMPH TJ (2019) Plant weight determines secondary fibre development in fibre hemp (*Cannabis sativa* L.). Industrial Crops and Products Elsevier, **139** 111493.

WHITMER S (2020) An evaluation of hemp production practices in the U . S . Desert Southwest, Iowa State University, Iowa, USA.

ŻUK-GOŁASZEWSKA K and GOŁASZEWSKI J (2018) *Cannabis sativa* L. – Cultivation and quality of raw material. Journal of Elementology **23** (3) 971–984. https://doi.org/10.5601/jelem.2017.22.3.1500.

CHAPTER 8 RECOMMENDATIONS FOR FUTURE RESEARCH

This chapter summarises the overall recommendations of the research summarised above. Some of these are detailed further in the chapters.

The mapping and species distribution modelling, crop modelling, and hydrological modelling highlighted the lack of in-situ or ground truth data available to develop and test the models used. It is highly recommended that more in-situ data are used, if available or attainable, so that the models developed i) can be more representative and account for greater detail of the complex Cannabis value chain, ii) will have improved output accuracy with more rigorously evaluation, and iii) will have wider applicability to different growing areas and strategies.

Rainfall data are a major source of uncertainty in simulation modelling, particularly in arid and semi-arid regions. Since uncertainty typically decreases with an increasing number of observations, longer climate records result in more reliable modelling. Since the climate data for each altitude zone (AZ) in the hydrological modelling ended in 1999, it does not reflect the anthropogenically induced changes in extreme climatological events that have occurred over the past 25 years. It is therefore recommended that the Altitude Zones Climate Database be extended with observed daily data by at least 20 years. This would not only benefit the streamflow reduction estimates for Cannabis but also for the forestry and sugarcane industries.

Need for field experiments: Field experiments should be conducted to estimate (i) seed yield, (ii) bud yield, (iii) fibre yield, (iv) accumulated biomass and (iv) water use. Such experiments should consider both (i) irrigated (i.e. non-stressed), and (ii) rainfed (i.e. stressed) growing conditions. Measurements should be conducted over several growing seasons until harvest. Ideally, the experiments should be repeated across different agro-ecological zones deemed suitable for *C. sativa* production. This will provide further information on the water productivity for the wide range of products available from the Cannabis plants.

The data described above would be invaluable to re-calibrate and validate the crop parameter files used in this project to improve the confidence in model simulations. Furthermore, observations of crop phenology in calendar days should be converted to Growing Degree-Days (GDDs), allowing AquaCrop to be run in GDD mode, which provides more realistic simulations of crop growth, yield and water use. The number of zero yield simulations should be used to calculate the risk of crop failure, which is defined as the number of zero yields divided by the number of simulated seasons, expressed as a percentage and provides an indication of financial risk.

Hydrological modelling: The seed and biomass yield maps produced in this research have provided an indication of the AZs that might be considered marginal for *C. sativa* production. However, it is more difficult to determine which zones are considered completely unsuitable for *C. sativa* cultivation. This was demonstrated by Kunz et al. (2024), who successfully used AquaCrop output to identify AZs deemed unsuitable for the production of sweet potato and taro by running the AquaCrop in GDD mode. Future work should also consider using AquaCrop simulations to develop land suitability maps for the cultivation of *C. sativa* biomass, fibre, seed and floral buds, which come from significantly different cultivars.

Further research is required to gather more evidence (i.e. measurements) for DWS to declare *C. sativa* cultivation as an SFRA. If this evidence conclusively shows *C. sativa* to be an SFRA, the government will need to limit (i.e. restrict) the spatial extent of *C. sativa* cultivation in order to minimise negative impacts on local and regional water resources.

Planting date can affect model simulations more than plant density. Owing to time constraints, only one planting date was considered (December). Using a variable planting date approach for each AZ is not recommended. Instead, the model should be run for a number of planting dates, namely September to January. This will provide a better understanding of crop response to planting date.

Economic analysis: Further analysis of the economic viability of *C. sativa* production in South Africa is required due to the wide range of varieties, agro-ecological areas, planting environments and products derived from Cannabis. Hemp's stem, which contains bast fibre, is of greater economic value than its woody core (for bioenergy). A cost-benefit (or break-even) analysis comparing input costs (e.g. seed, fertiliser, labour, water and land) versus benefits (income from the sale of fibre, seed and/or floral buds) is required. The analysis should factor in security costs related to fencing and alarm systems, which are required by law to protect the crop.

Socio-economic analysis: the key recommendations from the preliminary socio-economic analysis are:

- Develop clear, supportive legal pathways for small-scale cannabis cultivation.
- Create comprehensive programs for market access and skills development.
- Establish a multi-stakeholder approach to industry growth.
- Prioritize sustainable and ecological cultivation practices.

Policy recommendations: have been highlighted by Grooten (2023). These in addition to those from the project team's experience are summarised here for consideration:

- **Comprehensive Legislation**: Legalize cultivation, possession, and trade by smallholder farmers; promote partnerships with licensed companies; establish minimum pricing; include protections and market support for rural development.
- **Seed supply and disease authority**: Support the supply of quality seed or seedlings with guidelines on the different varieties planted for different products as well as the recommended use of herbicides and pesticides.
- **Capacity Building**: Educate government staff on cannabis value chains; quantify Mpondoland production; engage ancestral farmers for tailored support and business viability.
- **Farmers' Cooperatives**: Provide clear guidelines for forming and registering cooperatives; use local extension officers to facilitate group organization and serve as licensing contact points.
- **Market Development**: Ensure reliable markets for farmers; launch a pilot project integrating product development and market exploration in Mpondoland; collaborate with research institutions (e.g., CSIR) and firms like Afrimat for hemp-based products such as hempcrete masonry.

Economic Diversification: Explore niche cash crops and cannabis tourism opportunities; enhance Mpondoland infrastructure to support economic growth.

General recommendations: The modelling work presented in this report should be considered as a preliminary investigation of Cannabis water use and yield potential. This research has provided the first documented water use and water productivity results for Cannabis in South Africa as well as an indication of areas in which Cannabis is likely to be grown successfully outdoors. It has brought to light the complexities around Cannabis including legislation, sourcing seed, the significant differences between different varieties, the different products derived from cannabis plants as well as the general lack of documented research around cannabis. Measurement at the two sites in the EC and KZN should be expanded to include multiple seasons of water use and productivity as well as the impact of different varieties and watering regimes.

Additional measurements of LAI and biomass production over the growing season, including final biomass and seed/fibre yield at harvest, can then be used to re-calibrate and validate the crop parameter files used in this project. Observations of phenological growth stages in calendar days should be converted to thermal time to allow AquaCrop to be run in growing degree-day mode. This mode accounts for water and temperature stress effects on transpiration, biomass and yield. Overall, these recommendations will improve the accuracy and confidence of the model simulations.

Appendices

Appendix A. Capacity building

A.1 Postgraduate students capacity building with abstract for each student

Table A-1. Student researchers linked with this project

Student name	Degree	University	Supervisors
Kamva Zenani	MSc, graduated	RU	Kathleen Smart, Tony Palmer
Gary Denton	MSc, submitted thesis	UKZN	Alistair Clulow
Sindiswa Mbelu	MSc, registered (submitting by mid-2025)	UKZN	Samson Tesfay
Jamie Botha	PgDip, submitted thesis	RU	Jessica Cockburn

Abstract of thesis: Kamva Zenani (Rhodes U)

Cannabis spp is one of the oldest cultivated plants, with its origin in Asia. It has two species, namely *C. indica* and *C. sativa*. This research focuses on *C. sativa*, which is widely cultivated locally and globally. *C. sativa* has a wide range of uses, including industrial, medicinal, religious and recreational. In recent years, there has been a growing interest in increasing its cultivation, but there are reports of it having high water use. The global interest has led many governments to review the laws governing this plant as it is a controlled substance in many countries.

Due to its legal status, there is a dearth of knowledge about its growth and water use. It is against this backdrop that the Water Research Commission (WRC) commissioned this study into the water use of this plant. Our research seeks to measure water use under dryland cultivation. This will provide evidence-based support for the issuing of water use licenses by the Department of Water and Sanitation. The Eastern Cape and KZN have many small-scale legacy farmers who have been growing Cannabis illegally for decades. The findings of this research seek to fill some of these gaps and help legacy farmers expand their operations.

This research had four approaches, which include 1) planting the crop in a dryland location that will mimic the conditions experienced by legacy growers, 2) the collection of plant parameters in both dryland and tunnel-grown conditions in order to gain a better understanding of the plant's health, growth and progress, 3) the installing of a large aperture scintillometer together with a micro-meteorological station to measure the evapotranspiration over a crop cycle, 4) to use MEDRUSH transpiration model to predict the ET.

The results show that soil nutrient status and water provision had a significant impact on plant biophysical variables and water use. In the rain-fed field trial, plants received 154 mm (2 mm day^{-1}) of rain during the crop cycle. The large aperture scintillometer recorded a total ET of 126.8 mm (1.79 mm day^{-1}) during the same period. In the field trial, plants performed best in deeper, high-nutrient-status soils. They had higher leaf area index, width, height and stomatal conductance and were more vigorous than those that were grown in nutrient-deficient soils. During the peak of the growing cycle on January 3rd plants grown on high nutrient status mounds had a higher mean in all the bio-physical parameters, with a leaf area index (3.28±1.05), height (1.16±0.09 m), stomatal conductance (711.73±115.67 umol m^{-2} s^{-1}) and width (0.79±0.16 m) when compared to lower nutrient status soil with a leaf area index (1.70±0.79), height (0.83±0.16 m), stomatal conductance (665.5±169.38 umol m^{-2} s^{-1}) and width (0.45±0.25 m). The crops planted in grow bags and soil in tunnels received 2.5 and 4 l day^{-1}, respectively. It was also observed that plants that received un-limited nutrient-rich water had higher values in all parameters. This is evidenced by the plants grown in aquaponics. In the tunnels, outliers that were relatively short and less healthy had higher stomatal conductance, and this could be attributed to an inability to control stomatal conductance due to being under severe stress. The MEDRUSH model (2.5 mm day^{-1}) slightly overestimated the LAS ET (1.79 mm day^{-1}), and the results from the daily ET revealed that *C. sativa* had higher daily ET when compared to the local grass *Eragrostis plana.* These results confirm that *C. sativa* requires regular irrigation in order to grow and produce a crop. The study has shown that when combined with emergency drip irrigation, dryland production of *C. sativa* can produce a good yield and may not be as water-thirsty as previously thought.

Abstract of thesis (Draft): Sindiswa Mbelu (UKZN)

This study investigates the water use efficiency, morphological traits, and yield performance of *Cannabis sativa* under controlled pot trial conditions in KwaZulu-Natal, South Africa. The experiment was conducted in a greenhouse using the Cherry Wine strain, with plants grown in co-compost media and monitored using load cells for precise water use measurements. Morphological parameters, including plant height, leaf area, and root-to-shoot ratio, were evaluated alongside yield-related metrics such as bud mass and biomass. Findings reveal that the plants used an average of 81.8 mL of water per day, with water productivity values ranging from 1.49 L/kg to 4.1 L/kg, influenced by variations in bud mass. Specific Leaf Area (SLA) and Water Use Efficiency (WUE) were calculated to assess the effectiveness of water utilization, with WUE increasing alongside higher bud mass. The Harvest Index (HI) showed that Cherry win (plant D), with the highest bud mass (55 g), exhibited the greatest efficiency in allocating resources toward harvestable yield. Cold conditions and powdery mildew infestation were identified as constraints, leading to stunted growth and early senescence in some plants.

This research highlights the potential of *Cannabis sativa* Cherry wine as a drought- tolerant crop while emphasizing the importance of optimizing growing conditions and management practices to enhance water use efficiency and yield. These findings contribute to understanding Cannabis' adaptability to water-limited environments and its role in sustainable agriculture under changing climatic conditions.

Abstract of thesis (Draft): Gary Denton (UKZN)

The South African National Water Act (No. 36 of 1998) mandates the regulation of land-based activities that reduce streamflow by declaring them streamflow reduction activities (SFRAs). Hemp

(*Cannabis sativa* L.) is commonly known as a water-intensive crop, yet no measurements of its evapotranspiration (ET) exist in South Africa. Therefore, its impact on streamflow reduction cannot be assessed. This study provides ET data to determine if irrigated hemp should be investigated further as a potential SFRA by determining its ET and water productivity. An eddy covariance (EC) system was utilised in a hemp field trial at a commercial farm in KwaZulu-Natal (29°31’37.0” S, 30°28’03.2” E). Approximately 7 ha of hemp was planted on 21 November 2022 and harvested on 15 April 2023. Standard microclimatic variables and the volumetric soil water content, plant height and Leaf Area Index (LAI) were measured. To extrapolate the field measurement results beyond a point measurement to assess spatial difference in water use, a remote sensing modelling approach was applied to derive ET using multispectral drone imagery. It was found that although there is still a deficit in the modelling applications involving hemp, the QWaterModel was potentially a suitable modelling platform, chosen due to its operational simplicity. The EC measurements indicate that the total ET from the hemp crop over the growing period was 377 mm. The average daily ET was 2.94 mm plant^{-1} or 28.4 L tree^{-1}. The crop factor varied between 0.63 and 0.76 throughout the season and the water productivity of hemp (kg of fresh bud per m^{-3} of water) was 0.96 kg m^{-3}. Hemp had a high water use and low water productivity compared to other international hemp studies. This may be partly due to the higher planting density reported in other international studies (2 000 plants ha^{-1} vs. 300 000 – 2 400 000 plants ha^{-1}). The QWaterModel was found to overestimate ET over the growing season, with an accumulated ET_{QW} of 24.2 mm being modelled over five flights (five days) throughout the season, while the EC system measured approximately 16.9 mm ET_{EC} over the same period. However, a good correlation was observed between QWaterModel and ground-based EC measurements. The lack of canopy closure affected the estimation of ET, as the single-source QWaterModel is unable to differentiate heterogeneous canopies. The remote sensing approach depicted the variability of ET across the field, with higher ET taking place due to differences in topographical elevation, and therefore the soil depths of the field. These results provide the first water use and crop factor estimates of hemp in South Africa and provide data required to assess the streamflow reduction activity of hemp.

Abstract of thesis: Jamie Botha (Rhodes U)

This action research project investigates sustainable cannabis farming practices and knowledge exchange among legacy farmers in South Africa's Eastern Cape region. The research emerged from observations of informal knowledge transfer during a cannabis research project at Rhodes University's Institute for Water Research. Through a sustainability learning intervention implemented at the Township Cannabis Incubator in Mthatha, the study explored effective teaching methods and documented sustainable small-scale cannabis farming techniques. The intervention involved twenty participants, including municipal representatives, small-scale farmers, and university students.

Using a qualitative action research methodology, the study employed focus group discussions, questionnaires, and reflective journaling to examine two key questions: the relevance and effectiveness of sustainability learning processes in the local context, and insights for professional development in sustainability education. The findings highlight the importance of context-specific learning approaches, particularly regarding language and cultural considerations, and demonstrate

the value of co-productive agility in facilitating knowledge exchange. The research revealed how traditional farming knowledge can be effectively integrated with modern sustainable practices through participatory learning processes.

The study contributes to understanding how sustainability education can be more effectively implemented in marginalized farming communities, while highlighting the complexities of navigating power dynamics in knowledge co-production. It also provides insights into the challenges faced by legacy cannabis farmers in South Africa's evolving legal landscape, suggesting pathways for more inclusive and sustainable agricultural development.

A.2 Institutional capacity building

The WRC project has resulted in significant institutional and researcher capacity building on *Cannabis* water use. There have been benefits of departmental collaborations within and across universities.

A.3 Capacity building at the community level

The stakeholder engagement conducted by Mr Botha (presented in Chapter 7) included a component of capacity building. The engagement identified socio-economic indicators and barriers for the community particularly for market participation. There was strong community interest in adopting sustainable practices. The Learning and Teaching Support Materials used consisted of a printed information sheets with explanations of- and instructions on how to make your own black soldier fly frass and mycorrhizal fungi inoculum. In addition, fact-sheets on how to grow cannabis in dry-land conditions created by Anthony Palmer, that were translated into isiXhosa were shared that the participants could take home.

Before the engagement a WhatsApp group was created with a few of the leaders (including one of the Chiefs in the Mthatha area) and audio and visual presentations were created related to good practices for growing Cannabis (from literature and project research) and benefits of mycorrhizal fungi.

Appendix B. Ethical clearance certificate and survey questionnaire for stakeholder engagement

RHODES UNIVERSITY
Where leaders learn

Education Faculty Research Ethics Committee
Rhodes University
Education Building, Grey Street, Grahamstown/Makhanda, 6139, South Africa
PO Box 94, Grahamstown/Makhanda, 6140, South Africa
t: +27 (0) 46 603 8315
e: dean.education@ru.ac.za

22 June 2024

James Botha

Education Department

g14B4851@campus.ru.ac.za

Dear Mr James Botha

Re: EXPLORING KNOWLEDGE AND OPPORTUNITIES FOR LOCAL SUSTAINABLE INTERVENTIONS FOR INCREASING THE EFFICIENCY OF CANNABIS PRODUCTION

APPLICATION NUMBER: 2024-7622-8783

This letter confirms that your research ethics application has been reviewed and **APPROVED** by the Education Faculty Research Ethics Committee (EF-REC). Your permission letter(s) where applicable have been received and you are free to proceed with your study.

Approval is granted for 1 year. An annual ethics renewal application needs to be submitted each year. Should any substantive change(s) be made during the research process, that may have ethical implications, you should notify the Education Faculty REC Chair via email. This includes changes in investigators. The REC Chair will advise as to whether a new application is necessary.

Do keep this clearance letter secure and accessible throughout your study and after its completion. It will be needed when a thesis is examined and when publications are submitted to journals.

Please also submit a brief report to the REC Chair on the completion of the research. This can be done via email. The purpose of this report is to indicate whether the research was conducted successfully and whether any ethics-related matters arose that the committee should be aware of, in order to guide future studies.

Sincerely,

MBlackie

Prof Mags Blackie

Chair: Education Faculty Research Ethics Committee

B.1 Questionnaire: Understanding legacy Cannabis farming practices

Introduction: Thank you for participating in this survey aimed at understanding the challenges and opportunities faced by small-scale cannabis farmers in (*Name of area*). Your insights are invaluable in shaping support initiatives and promoting sustainable practices. Please take a few moments to answer the following questions.

1. Can you describe your experience with cannabis cultivation and how long you've been involved in it? If you have interest in growing cannabis and have not done so far, please answer the questions below from that perspective.

2. What specific challenges do you face in cultivating cannabis on a small scale?
3. What varieties or cultivars of cannabis do you typically grow (or intend to grow), and why?
4. How do you (or will you in future) handle issues related to crop selection, such as deciding between CBD oil, medical, or hemp varieties?
5. How do you currently manage environmental concerns such as water usage and pesticide application?
6. What traditional farming practices do you (or will you) incorporate into your cannabis cultivation, and how effective have they been?
7. How do you envision sustainable practices benefiting your cannabis farming operation?
8. How do you see your farming practices evolving in the future, considering sustainability concerns?
9. Are there any specific techniques or innovations you've implemented to enhance sustainability on your farm?
10. What role do you believe indigenous or local knowledge plays in cannabis cultivation?
11. Have you participated in any knowledge-sharing or capacity-building initiatives related to sustainable agriculture? If yes, can you share some information on what these initiatives were and what knowledge you gained?
12. What are your thoughts on the potential for collaboration among small-scale cannabis farmers in your region? What sort of collaboration would this include?
13. How do you perceive the impact of policy ambiguity on your cannabis farming operations?
14. How do you navigate challenges related to registration processes or regulatory compliance for cannabis cultivation?
15. Can you share your insights into accessing markets for your cannabis products?
16. What resources or support do you feel are lacking for small-scale cannabis farmers in your community?
17. What support or assistance do you think would be most beneficial for small-scale cannabis farmers like yourself?
18. How do you perceive the cultural significance of cannabis cultivation in your community?
19. How do you envision the future of small-scale cannabis farming in your region, considering both opportunities and challenges?

Conclusion

Thank you for your participation. Your feedback will help inform efforts to support small-scale cannabis farmers in our community. If you have any additional comments or insights you'd like to share, please feel free to do so below.

Demographic Information: (Optional)

- Age:

- Gender:
- Years of Experience in Cannabis Cultivation:
- Size of Farm (in acres/hectares):
- Additional Comments (Open-ended):

Appendix C. Survey instruments

Table C-1 List of instruments at the LAS Micro-Meteorological Station used by Mr Zenani in the Eastern Cape

Bio-meteorological variable	Instrument
Soil heat flux ($W.m^{-2}$)	4 x soil heat plate (HFP01), (Hukseflux Thermal Sensors, Delft, Netherlands)
Volumetric water content (%)	Water content reflectometer (CS616, Campbell Scientific Inc., Logan, Utah, USA)
Temperature and RH (%)	HC2S3 Temperature and RH Probe (Campbell Scientific Inc., Logan, Utah, USA)
Soil temperature (°C)	2 x Averaging soil thermocouples probe (TCAV, Campbell Scientific Inc., Logan, Utah, USA)
Net radiation ($W.m^{-2}$)	2 x net radiometers (NR-lite2) (Kipp and Zonen, Netherlands)
Air temperature (°C)	2 x fine wire thermocouples (FW05: 0.0005 inch /0.0127 mm, Campbell Scientific Inc., Logan, Utah, USA) at 1.0m and 2.5m above soil surface
Wind speed ($m.s^{-1}$) and direction (degrees)	Wind Monitor-AQ, model 05305, R.M. Young Company, Michigan, USA

Table C-2 Instruments included in the eddy covariance system used by Mr Denton

Instrument	Measurement	Manufacturer
CS616 Water Content Reflectometers	Volumetric soil water content	Campbell Scientific, Logan, Utah, USA
EC150 CO_2/$H_2$0 Open-Path Gas Analyser	CO_2/$H_2$0 flux	Campbell Scientific
HFP01 Soil Heat Flux Plate	Ground heat flux	Huxaflux, Delft, Netherlands
CSAT3A Three-Dimensional Sonic Anemometer	CO_2/$H_2$0 flux	Campbell Scientific
TE525mm Tipping Bucket Rain Gauge	Rainfall	Texas Instruments, Dallas, Texas, USA
HC2S3 Temperature and Relative Humidity Probe	Temperature; relative humidity	Campbell Scientific
CNR4 Net Radiometer	Net solar radiation	Kipp and Zonen, Delft, Netherlands
FW1 Type E fine wire thermocouples	Air temperature	Campbell Scientific
TCAV Type E thermocouples	Average soil temperature	Campbell Scientific

Appendix D. Experimental design and layout at Sweetwaters

D.1 Background

Cannabis sativa plants from clonal material (*Exodus cheese*) were provided by Cannabiol, Australia. The plants were cultivated for export to Cannabiol where they were sold to the legal medicinal cannabis market.

The Sweetwaters Cannabis Facility owned by Labat Africa Pty Ltd is a licensed *C. sativa* growing facility located in the small Eastern Cape coastal town of Kenton on Sea. Sweetwaters is located a couple of meters from the banks of the Bushman's River and about 3.2 kilometres from Kenton on Sea Central Business District on the R343 road towards Makhanda (GoogleEarth, 2022).

Figure D-1 A tunnel in Sweetwaters Facility, this is an example of aquaponics, whereby plants are immersed in water

D.1.1 Germination

Cannabis sativa seeds were soaked in different jars of water for 24 hours. After 24 hours the seeds were placed between a double-folded paper towel, damp and cover with cling wrap. The next step was to germinate the seeds that have roots in trays that were filled with a mixture of cannabis soil mixture and growing powder.

D.1.2 Treatments

The Sweetwaters Cannabis Facility has three different treatments. The main difference between the treatments is the amount of water each treatment gets. The first treatment plants are planted in the local soil in a tunnel/greenhouse with an AH24 shade-cloth cover. The greenhouse enables the growing plants to have extinction of photosynthetically active radiation equal to 50% and all the plants are clones. These plants have a drip irrigation system installed and they receive four litres of water every hour. The second treatment is a similar tunnel with the same properties. The plants are grown in a soil, soldier-fly frass and mulch mixture in 40 litre grow bags. These plants receive 5 litres of water every day. These plants have scrog netting installed on top of them. The third treatment is aquaponics, where the plants are placed in 20 litre buckets that are filled with aggregate rocks made from quartzitic sandstones. Water was constantly being fed into the buckets for 24 hours; this treatment received the most water.

D.1.3 Biophysical monitoring

The main goal of biophysical monitoring is to produce long-term data for the planting of *Cannabis sativa* and producing the best yield for local and international markets. The facility monitors the amount of water used in the irrigation of the plants, especially the plants planted in the soil. It also monitors the water pH in aquaponics, monitors total dissolved solids (TDS), monitors the amount of nutrients such as calcium, potassium and magnesium and if the amounts are low, the nutrients are added. Water temperature is also monitored. The soil pH is about 7, which is perfect for nutrient uptake and plant growth (Shannon Booth, pers. comms, 2022).

D.1.4 Data collection

Data collection at Sweetwaters Cannabis Facility commenced in June 2022 and ended in August 2022. The data was collected using a hand-held leaf porometer for measuring stomatal conductance, a ceptometer to measure leaf area index and photosynthetically active radiation and a tape measure to measure the height and width of the plants. The data was measured on three separate occasions. The data was collected from three different treatments. The treatments differ according to the amount of water they receive and the growing medium. Some are grown in aquaponics while others directly in the soil and others in bags

D.2 Results

The stomatal conductance from three different treatments varied. The aquaponics treatment exhibited the highest stomatal conductance values while the plants grown in bags exhibited the lowest values in (Figure D-2).

The leaf area index (LAI) also varied among the different treatments the plants were growing under. The plants grown in bags exhibited the highest LAI while the plants grown directly in the soil exhibited the lowest LAI.

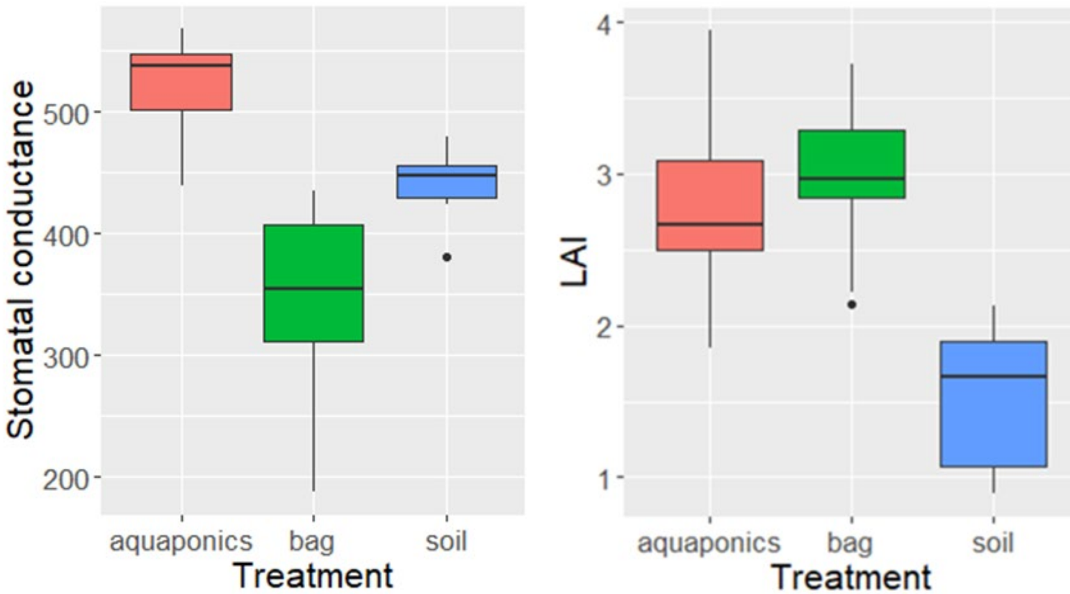

Figure D-2 Stomatal conductance and Leaf Area Index of each treatment at Sweetwaters

The plant height and width data were collected at Sweetwaters during the same period as the other two measured parameters viz LAI and g_s. The plants planted in the soil had the tallest plants followed by those planted in aquaponics. The width of the plants followed a similar trend to the height, with plants planted on the grass having the highest value for width followed by aquaponics and lowest value for width was found in the plants planted in bags.

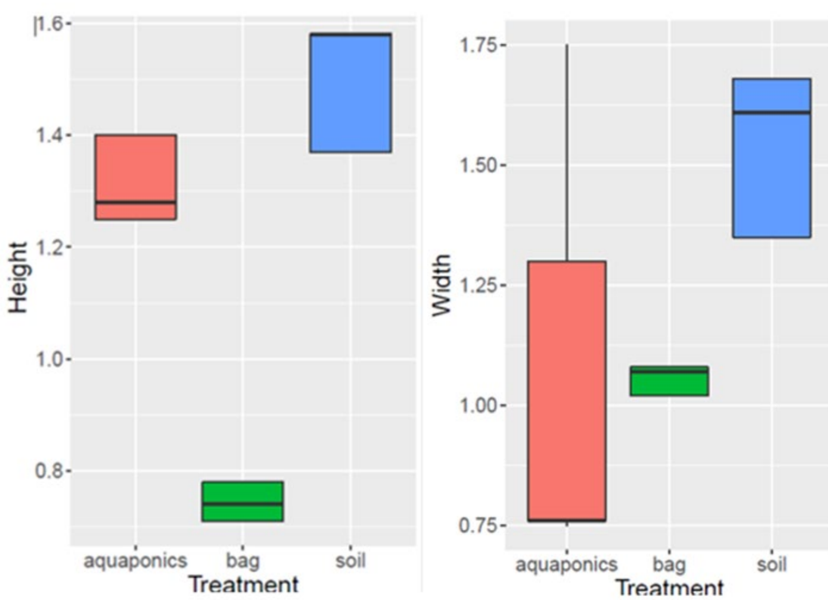

Figure D-3 The average height and width of Cannabis sativa in meters

D.3 Discussion

The aquaponics treatment exhibited the highest stomatal conductance. This can be attributed the amount of water the plants under this treatment receive which is significantly higher (submerged in water) when compared to the other two treatments bags and soil which receive 2.5 litres a day and 4 litres per day when temperatures are very high for six hours respectively. It can therefore be deduced that there is a strong correlation between the amount of water a plant receives and the stomatal conductance because when water is plentiful plants can afford to keep their stomata open in order to facilitate photosynthesis (Farquhar and Sharkey, 1982, Damour et al., 2010). The plants that are planted in the soil had the second highest stomatal conductance, this further corroborates the findings that suggest that plentiful water or water availability leads to high stomatal conductance because plants in the soil received the second largest amount of water. *C. sativa* plants that receive plentiful water are usually healthier than those who are water stressed because plants are able to perform at optimum level and processes like photosynthesis are also working at optimum level also.

Appendix E Crop parameters

Table E-1 AquaCrop parameters for hemp

No.	Crop parameter	Wimalasiri (2023)		Averink (2015)
		Fibre	Seed	Seed
05	Crop is	sown	sown	sown
08	Base temperature for no crop development (°C)	1.5	1.5	0.0
09	Cut-off temperature for no crop development (°C)	40	40	15
	Soil water depletion (stress) factors for:			
11	- canopy expansion (upper threshold)	0.25	0.25	0.30
12	- canopy expansion (lower threshold)	0.55	0.55	0.60
14	- stomatal control	0.50	0.50	
16	- canopy senescence	0.60	0.60	
19	- pollination/flowering	0.90	0.90	
	Shape factors for:			
13	- canopy expansion	3.0	3.0	
15	- stomatal control	3.0	3.0	
17	- canopy senescence	3.0	3.0	
39	- root zone expansion	13	13	
35	Basal crop coefficient	0.96	0.96	
37	Minimum effective rooting depth (m)	0.30	0.30	
38	Maximum effective rooting depth (m)	2.00	2.00	
43	Soil surface area covered by plant at 90% emergence (cm^2)	5.00	5.50	
44	Canopy size of individual plant (re-growth) at 1st day (cm^2)	5.00	5.50	
45	Number of plants per hectare	300 000	140 000	2 500 000
46	Canopy growth coefficient (CGC in % day^{-1})	11.917	11.150	7.900
50	Maximum canopy cover (CC_X)	0.90	0.85	0.95
51	Canopy decline coefficient (CDC in % day^{-1})	9.615	9.815	7.770

	Calendar days from sowing to:			
52	- emergence/recovered transplant	10	10	7
53	- maximum rooting depth	60	60	
54	- start of senescence	105	100	100
55	- physiological maturity (length of crop cycle)	140	135	120
68	- start of yield formation/initiation			
58	Crop determinacy unlinked with flowering	0	0	
56	Calendar days from sowing to flowering	89	89	
57	Length of the flowering stage (days)	12	17	
59	Buildup of harvest index (%)	20	20	
60	Length of harvest index buildup period (days)	90	90	
61	Normalised water productivity (WP* in g m^{-2})	15	15	15
62	WP normalised for ET_O and CO_2 during yield formation (%)	25	25	
64	Reference harvest index (HI_O in %)	10	18	35