MAPPING WOODY INVASIVE ALIEN PLANT SPECIES AND THEIR IMPACTS IN STRATEGIC WATER SOURCE AREAS

Report to the

WATER RESEARCH COMMISSION

By

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EXECUTIVE SUMMARY

In South Africa we are running out of water fast, water quality continues to decline, and our population size continues to grow. Despite water being a limited and precious resource, we are allowing a significant amount of our water resources to be consumed by alien trees. These alien trees not only guzzle water, but also decimate biodiversity and cause severe fires, and they are spreading rapidly. The United Nations has named the next ten years the ‘decade of ecological restoration’ because our well-being depends on healthy nature.

BACKGROUND AND RATIONALE

In South Africa alone, the value of nature’s benefits to people is around R275 billion annually (about 7% of our GDP). These alien trees cost the nation R6.5 billion annually, and government spends R300 million annually clearing alien trees. It is estimated that approximately 14% of the invasions in South Africa have been demarcated for awarding clearing contracts. However, the return on investment has not always been clear, and success has been patchy (van Wilgen et al. 2022). One reason for this is lack of information on alien trees: where they are, and how fast they are spreading. This is exactly what this project proposed to address. Using cutting-edge technology and satellite imagery, up-to-date, fine-scale (10 m), low-cost maps were produced for important and data scarce strategic water source areas in South Africa, and the impact on water resources estimated using satellite-derived products. Restoration (effectively clearing alien trees) would improve nature’s resilience (preventing tipping points being reached). Ecosystems could therefore better absorb shocks and buffer communities from sudden or long-term changes expected from climate change, improving water security.

This project had two main aims: (1) to map woody invasive alien plants using freely available satellite imagery and field data in selected strategic water source areas in South Africa, and (2) to estimate the water use of woody invasive alien plants relative to native vegetation using freely available satellite imagery in strategic water source areas in South Africa. The specific objectives were: (1) to map the occurrence and distribution of target invasive alien plants within the selected strategic water source areas, (2) to map the density (percentage cover) of target invasive alien plants within the selected strategic water source areas, (3) to estimate the age of the identified invasive alien plant stands within the selected strategic water source areas, (4) to estimate evapotranspiration spatially for indigenous compared to invasive alien plants for the selected strategic water source areas, and (5) quantify impacts on water and compare results to the available literature.

The use of freely available remote sensing imagery and products holds utility for resource constrained regions where there is no budget for airborne campaigns. Freely available Sentinel-2 imagery is accessible at a 10 m spatial resolution, and has been successfully used to map invasive alien trees in certain biomes in South Africa before this (Holden and Rebelo et al. 2021; Rebelo et al. 2021). The question is: is this approach valid in other bioclimatic regions, and could this approach be upscaled to produce a national invasive alien tree map? In addition, other information on invasions is also required, such as invasion density (percentage cover) and vegetation age as this determines the type of restoration applied, and the water-related benefits of clearing. The latter may be very useful for making the case for restoration, either to raise investment for restoration, or to leverage more

traditional grant funding. Investment requires evidence of the benefits of restoration, and therefore better estimates of the relative impacts of invasive alien trees on water are required.

Invasive alien trees are known to have the largest negative impact on ecosystems (e.g. biodiversity, fire regimes, soils, water and carbon) due to a change in growth form dominance from indigenous grassland, or shrubland, to stands of trees. However, some shrubs (e.g. Bugweed) and even herbaceous species (e.g. *Lantana camara*) have been shown to have higher water-use relative to their grassland counter-parts (Meijninger and Jarmain 2014). Therefore, we hereafter refer to our taxa of interest as “woody invasive alien plants” rather than “invasive alien trees”.

METHODOLOGY

To produce maps of woody invasive alien plants, methods developed by Holden and Rebelo et al. (2021) were applied in this study and tested further in the different biomes (savanna and grassland) and climate regions (temperate, arid) of the selected study sites: Luvuvuhu, Sabie-Crocodile, Tugela and uMzimvubu. Starting with stakeholder engagements to determine invasive alien taxa of importance, fieldwork was then planned and conducted, using a pure pixel approach, and datasets of geotagged photos and metadata were processed and finalized. Platforms used included Cybertracker and ArcGIS Pro, and photos were archived on iNaturalist in a specifically designed project. Classifications were then performed using free cloud computing (on Google Earth Engine), and validation and independent ground truthing done. Ethics approval was granted through Stellenbosch University (FESCAGRI-2022-26880; FESCAGRI-2022-26881).

To estimate density (percentage cover) of woody invasive alien plants in all the study catchments, three different indicators were developed and sense-checked against a small sample of field estimates. To estimate vegetation age, age (years) was calculated from the most recent fire, in the MODIS Burned Area Monthly Global 500 m dataset in Google Earth Engine (MCD64A1.061).

For the water-use impacts of invasive alien trees, we started with assembling flux tower data from researchers and organizations in South Africa, yielding a rich dataset of 14 flux towers. These were used to validate a selection of remotely sensed and derived evapotranspiration products in different bioclimates. The best performing evapotranspiration products were combined into an ensemble model, and these results were run for each of the four study catchments. Various metrics were calculated, such as the relative water-use among land-use/land-cover classes, the relative difference inside and outside of strategic water source areas and whether this has a bearing on impact, and the potential water gains (volume of water) were calculated. These findings can be used to help guide decisions around shifts in agricultural or land-use type (e.g. from plantations to another more water-friendly crop), and they may also be used to secure investment, as the results provide evidence of the benefits of restoration.

MAIN FINDINGS

Invasive alien trees and plantations collectively make up between 2-23% of the four catchments studied, most of which were located within strategic water source areas. Overall accuracy (for all classes) ranged from 87-95%, and 96-98% when discriminating alien classes from all non-alien classes (n=2). Results show that woody invasive alien plants cover over 6% of the Luvuvhu Catchment either in the form of plantation forestry, or alien invasions. Other Invasive Alien Plants seem to be the most extensive class, covering an estimated 160 km^2. Pine and gum cover an estimated 47 km^2 and 87 km^2 respectively, the majority (69%) within the strategic water source area. Woody invasive alien plants cover over 23% of the Sabie-Crocodile Catchment either in the form of plantation forestry, or alien invasions. Pine and gum cover the largest areas, with an estimated 553 km^2 and 464 km^2 respectively. Bugweed also covers an extensive area of 131 km^2, while it is noted that there may be far more extensive unmapped below canopy invasions that are not detectable by optical satellite remote sensing. Most of the invasions and plantations (96%) are within the strategic water source area.

For the Tugela Catchment, woody invasive alien plants cover 2% of the surface area either in the form of plantation forestry, or alien invasions. Wattle and gum cover large areas, with an estimated 54 km^2 and 36 km^2 respectively. Poplar invasions are harder to successfully map, as they occur in narrow strips on either sides of rivers, however this project suggests about 40 km^2 invasion of poplar in the Tugela Catchment, bearing this caveat in mind. Most of the invasions and plantations (80%) fall within the surface water strategic water source area. For the uMzimvubu Catchment, woody invasive alien plants cover over 7% of the surface area either in the form of plantation forestry, or alien invasions, but mostly the latter. Silver and Black/Green Wattle cover the largest areas of the catchment, estimated at 485 km^2 and 329 km^2 respectively. Gum and pine are also prolific invaders in the catchment. Most of the invasion (68%) is within the surface water strategic water source area of the catchment.

The trialled method to calculate plant density (percentage cover) using probability as an indicator was not sufficiently accurate and therefore another approach will need to be trialled in future. Likewise the MODIS burned area dataset, used to produce an indicator for vegetation age, had many gaps for the catchments of interest, and although there was some relationship between vegetation age derived from MODIS and the field estimates, this does not seem to be the most robust approach. These methods were based on observations from the Cape, and it is possible that they do not transfer well from the fynbos biome.

In terms of water-use, across all catchments, the trees such as pine, gum and wattle had the highest evapotranspiration relative to all other classes. Interestingly, the highest water using taxon is not the same across all catchments, though in two cases gum has the highest water use of all other classes. In terms of rainfall-evapotranspiration ratio, between 80-87% of all rainfall is evapotranspired according to our results. Our results also show that the relative impact of invasive alien trees on water is not necessarily higher within strategic water source areas. Relating these estimates back to the literature, our research has shown that the MAPWAPS-derived evapotranspiration values are marginally lower than the published literature, suggested by the percentage bias (PBIAS) values of around -15. This slight underestimate would have little effect on the relative values of evapotranspiration.

In the Luvuvhu Catchment, the largest potential gains in water were from a transition from invasive alien trees such as gum, pine, but also from Bugweed to indigenous vegetation classes and dryland (rainfed) agriculture. Differences between invasive alien pines and gum, and dryland and irrigated agriculture, and Mopane-dominated indigenous bush were around 300 mm/a. In the Sabie-Crocodile Catchment, a shift from pine or gums to any indigenous or agricultural classes could produce a gain ranging from 23-123 million m^3 (40-232 mm/a). This excludes indigenous forest which uses the same amount of water on average as pine and gum plantations and invasions. In the Tugela Catchment, a transition from gum, pine, wattle or poplar, to indigenous classes (excluding Vachellia-dominated indigenous bush and indigenous forest) or dryland agriculture could produce water in the order of 29-100 mm/a. In the uMzimvubu Catchment, gum and pine are commercial plantations or woodlots whereas the wattle (Black/Green and Silver Wattle) is mainly invasions. There are potentially very large water benefits if all the wattle are cleared, cumulatively 76 million m^3 (74-107 mm/a) if they are restored to grassland and wetlands, which they have largely invaded. For all catchments, the water-use of indigenous forest was lower than pine (Luvuvhu, Tugela), gum (Sabie-Crocodile, Tugela), and wattle and poplar (Tugela).

In summary, this project has delivered a method to map woody invasive alien plants with high accuracy, and this utility and accuracy has been demonstrated in several different biomes. Additionally, this project is one of the first of its kind in South Africa to firstly map evapotranspiration spatially and temporally and interrogate the results for various land-use classes, but then secondly to also validate these results based on a network of flux tower data. Further to this, we have also used only open-access, freely available evapotranspiration products. This means that our output is therefore readily usable and cost-effective for resource constrained nations. The MapWAPS Project has demonstrated that the remote sensing method to map woody invasive alien trees originally developed in the Fynbos Biome by Holden and Rebelo et al. 2021 is highly adaptable and performs well in multiple other biomes. These findings suggest that this approach could feasibly be used to develop a national woody invasive alien plant map that is both cost-effective and easily repeatable.

RECOMMENDATIONS

We propose the following recommendations:

1. Clearing woody invasive alien plants in strategic water source area catchments and restoring to indigenous classes has major water-related benefits.
2. Besides the issue of woody invasive alien plants, the presence of plantations within strategic water source area catchments presents a trade-off that requires further debate around water-use licensing in water scarce catchments.
3. Improving compliance to control escapees from invasive alien trees plantations should be prioritized.
4. Plantation forestry should exit from riparian zones and wetlands in line with legislation, and this transition should be enforced and expedited and the certification process improved.
5. Sustainable investment (finance) into invasive alien tree clearing is critical. There needs to be a long-term (e.g. 20-to-50-year timeframe), strategic vision and programme with collaboration of all sectors and stakeholders.
6. Ecological expertise is a scarce skill, and investment into ecological training is recommended.

We outline the following opportunities for future research and innovations:

1. Investing in the production of an annual invasive alien tree map for South Africa using remote sensing combined with ecological expertise should be a national priority.
2. All training data collected for invasive alien plant mapping should be centrally archived and curated, such that future mapping efforts can be improved nationally.
3. The relative impacts of different land cover types on evapotranspiration should be further studied, using remote sensing derived data, but also powerful statistical techniques to account for confounding variables.
4. A tool to estimate the impacts of land-use/land-cover decisions using satellite remote sensing products should be developed for South Africa in line with stakeholder needs.

Frequently updated national invasive alien tree maps are critical to inform restoration efforts at a national scale. Our report pilots a method that achieves high accuracy in all selected study sites (varying bioclimates). Our method combines powerful machine learning techniques with ecological expertise. The importance of ecological expertise in achieving high accuracy cannot be understated, and this is a scarce skill that should be invested in. These maps would also serve to feed into reporting on the National Biodiversity Assessment as well as international reporting under the Global Biodiversity Targets. As a resource constrained nation, South Africa should leverage freely available remote sensing products for improved water resource management for the benefit of nature and people.

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DEDICATION

This report is dedicated to Prof David le Maitre, who was an original member of this project team, and an inspiration for this work in many ways. His loss was a great one for the country, and undoubtedly this project would have looked different had we been able to draw from his considerable knowledge for the outputs and bringing everything together. We did the best we could in his absence, and this work is dedicated to him.

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LIST OF ACRONYMS AND ABBREVIATIONS

ARC	Agricultural Research Council
DFFE	Department of Forestry, Fisheries and the Environment
IAP	Invasive Alien Plant
IAT	Invasive Alien Tree
GPS	Global Positioning System
LULC	Land-use/land-cover
MAPWAPS Project	"Mapping woody invasive alien plants and their impacts" Project
MODIS	The Moderate Resolution Imaging Spectroradiometer
NIAPS	National Invasive Alien Plant Survey
NDVI	Normalized Difference Vegetation Index
PBIAS	Percentage Bias
Sabie-Croc	Sabie-Crocodile Catchment
SPOT	Satellite pour l'Observation de la Terre
SUN	Stellenbosch University
SVM	Support Vector Machines
SWSAs	Strategic water source areas
UCP	uMzimvubu Catchment Partnership
WRC	Water Research Commission

Note on taxonomic conventions: Common names were capitalized for the full names of specific species, e.g. "Black Wattle", which are proper nouns. Where the genus was referred to, lower case was used, e.g. "wattle", i.e. common nouns. Class names were capitalized, e.g. "Wattle".

1. INTRODUCTION

Invasive alien plants are estimated to cost the South African economy R6.5 billion each year and are threatening up to 30% of the water supply of major cities along the southern coast (van Wilgen and Wilson 2018). Woody invasive alien plants are estimated to have high water-use, reducing surface water resources by 3-5% nationally, with a conservative total reduction in streamflow of 1 444 million m^3·annually (Le Maitre et al. 2016; Skowno et al. 2019). These challenges are amplified in a water-scarce, arid nation which faces considerable water challenges in terms of supply and quality. Given the uncertainty around climate change impacts, it is essential to restore ecosystems to improve resilience of the water supply to cities and rural communities (Dieppois et al. 2016; Skowno et al. 2019). Restoring ecosystems is also in line with global prerogatives, such as the United Nations Decade on Ecological Restoration, which started in 2021.

To partially control the invasive alien plant problem, the South African government is investing about R300 million a year in clearing invasive alien plants (van Wilgen and Wilson 2018). The programme has faced challenges in terms of reducing and halting the spread of invasive alien species, for various reasons, and the problem continues to grow (van Wilgen and Wilson 2018). There is an inadequate understanding of the current extent and severity of invasions in South Africa and how to predict and prevent future invasions (Skowno et al. 2019). This highlights the urgent need for focused monitoring of invasive alien plants and enhanced spatially explicit data on the extent and severity of invasions to inform management and improve planning (Skowno et al. 2019). Short of a full national inventory, there is a need to prioritize efforts in addressing the gaps. Ecological infrastructure (naturally functioning ecosystems that deliver ecosystem services) has been identified as a natural asset at risk, and particularly for a water stressed nation, there is a prioritized focus on strategic water source areas (areas of land that supply a disproportionately large quantity of surface water runoff in relation to their size) (Le Maitre et al. 2018). Within these strategic water source areas, in biomes with regular fires (that cause rapid ecosystem changes), there is a need for finer-scale, rapidly updatable invasive alien plant maps to guide managers and policy makers at both the national (DEFF-NRM) and local levels (Cheney et al. 2018; Holden et al. 2021).

In invasion-related research and management in South Africa, densities of woody invasive alien plants estimated in 2010 are still commonly used, as well as managers' estimates, which may be overestimates (Cheney et al. 2018). Although there have been significant advances in applied remote sensing in the last decade, and increased availability of free satellite imagery, this has not yet been fully harnessed for invasive alien plant management in the nation (Royimani et al. 2019). Indeed, satellite data are said to be underused within the biodiversity research and conservation communities (Turner et al. 2015). Some pilot studies have shown the potential use of freely available satellite imagery for detecting invasive alien trees in the Fynbos Biome (Holden et al. 2021) and detecting woody invasive alien plants at local scales in the Grassland Biome (Rajah et al. 2018). There is great potential to combine free satellite imagery (e.g. Sentinel-2, SPOT6&7) with advanced machine learning algorithms using the processing power of free platforms like Google Earth Engine, to produce high quality outputs for developing nations struggling with funding and the management of invasive alien plants (Royimani et al. 2019).

In addition, important knowledge gaps in the water-use of invasive alien plants relative to native vegetation have been highlighted (Le Maitre et al. 2015). The effective management of water resources in semi-arid regions requires accurate estimations of the major components of the hydrological cycle, particularly evapotranspiration (Dzikiti et al. 2019). Despite the importance of evapotranspiration (often amounting to 70% of rainfall in arid regions), it is hard to measure, and there is a paucity of data available to parametrise hydrological models relating to woody invasive alien plants (Le Maitre et al. 2015). There has been much research on the evapotranspiration of plantations and various agricultural crops, but far less on infestations of invasive alien plants, which are more complex given that they are patchy in distribution and often co-occur with native species, so are often not mono-specific stands, and that water-use varies with density and age (Meijninger and Jarmain 2014; Le Maitre et al. 2015). The implication is that the accuracy of hydrological models in estimating the impacts of woody invasive alien plants on water resources is compromised, with consequences for management, decision-making, policy and investment (Dzikiti et al. 2019). Strengthening the evidence-base for the benefits of clearing woody invasive alien plants on water resources, would also support efforts to leverage private sector investments to restore ecosystems.

1.1. Project aims

This project had two aims, and five objectives:

Aims

1. To map woody invasive alien plants using freely available satellite imagery and field data in key strategic water source areas in South Africa (Work package 1).
2. To estimate the water use of woody invasive alien plants relative to native vegetation using freely available satellite imagery in key strategic water source areas in South Africa (Work package 2).

Objectives

1. Map the occurrence and distribution of target invasive alien plants within the key strategic water source areas.
2. Map the density of target invasive alien plants within the key strategic water source areas.
3. Estimate the age of the identified invasive alien plant stands within the key strategic water source areas.
4. Estimate evapotranspiration spatially for indigenous compared to invasive alien plants for the key strategic water source areas.
5. Quantify impacts on water and compare results to the available literature.

2. KNOWLEDGE REVIEW

Remote sensing and data applications for better understanding invasive alien plant impacts

Invasive alien plants have been introduced in South Africa for many reasons, including timber (Richardson 1998; Enright 2000; Görgens and Van Wilgen 2004), soil stabilisation (Hellstrom and Lubke 1993), livestock feed production (Shackleton et al. 2007), and ornamental plantings in gardens (Enright 2000; Foxcroft et al. 2007). Many of these woody plant species have become invasive and cause serious negative impacts with concomitant economic consequences (Latimer et al., 2004; Le Maitre et al., 2002; Mostert et al., 2017). Negative impacts include: (i) water use impacts (Calder & Dye, 2001; Dzikiti et al., 2013; Le Maitre et al., 2000, 2015, 2016; Preston et al., 2018; Rebelo et al., 2022); (ii) increased fire risk (Brooks et al., 2004; Kraaij et al., 2018); (iii) decreased biodiversity and ecosystem services (Rai & Singh, 2020; Latimer et al., 2004; Pyšek et al., 2020); (iv) increased erosion and impacts on soils quality (such as impacted biogeochemical cycling, allelopathic impacts on native vegetation, impacts on symbiotic microbes and soil nutrients) (Ehrenfeld, 2003; Jacobs et al., 2020 Lubke, 1985; Majewska et al., 2018; Naudé, 2012; Raizada et al., 2008; Tererai et al., 2013); and (v) health impacts (Münch et al. 2019; Venter et al. 2020) or reducing rangeland productivity (Ndhlovu et al. 2011). These negative impacts have compounded over time with far-reaching implications for South Africa’s economy, society and ecosystems (van Wilgen et al., 2022).

Research on invasive alien plants to date has focussed on better understanding invasive alien plant population dynamics and their associated impacts. Many studies have documented the seriousness of invasive alien plant impacts and proposed strategies for management (Blignaut & Aronson, 2020; Le Maitre et al., 2020; Moyo et al., 2021; Novoa et al., 2018; Richardson, 1998). Previous studies have used field work campaigns to map invasive alien plants and quantify their impacts, but this can be very expensive, time consuming, and generally falls short of the scale that is required to satisfy regional and landscape level planning (Le Maitre et al. 2014; Abutaleb et al. 2021). These mapping efforts have also typically been unable to keep pace with the rates of spread. However, in more recent years (especially over the past decade), there have been developments in remote sensing techniques and data analyses to enable the mapping of invasive alien plant populations and to assess their impacts at scale (Royimani et al., 2019, Holden et al., 2021; Rebelo et al., 2021). There is a growing need to explore the advanced technology and data available to map the extent of invasive alien plants at more refined scales and to understand their impacts at landscape levels (Abutaleb et al., 2021; Holden et al., 2021; Rebelo et al., 2021). The use of novel and refined remote sensing applications is key in ongoing research to generate accurate invasive alien plant maps. This is useful for informing invasive alien plant management operations that are effective, environmentally compatible, and context specific.

This literature review therefore sets out to explore both the utility and limitations of various remote sensing techniques used to map invasive alien plants and their relative impacts. The literature review is comprised of three sections. The first section reviews the evolution of remote sensing in mapping invasive alien plants focusing on the key technologies developed to remotely sense invasive alien plants. The second section reviews how the density of invasive alien plant populations can be determined ex situ using remote sensing. The third section reviews the techniques used to determine invasive alien plant water use impacts.

2.1. Mapping invasive alien plants using remote sensing

2.1.1. The importance of mapping invasive alien plants

Mapping vegetation types aids understanding of ecosystems and landscapes (Egoh et al. 2008). Mapping vegetation has advanced from digitization (Lydersen and Collins 2018) to mapping in Geographic Information Systems (GIS) (Kadmon and Harari-Kremer 1992), to remote sensing classifications, both active and passive (Royimani et al., 2019). Active remote sensing refers to the emission of radiation from a sensor (i.e. Radar, LiDAR, and Scatterometers); while passive remote sensing refers to the measurement of the interaction of electromagnetic radiation from the sun with various surfaces on the Earth (i.e. Multispectral and Hyperspectral spectrometers and Radiometers) (Peters et al. 2020). Both active and passive remote sensing have been used to distinguish vegetation types or land uses from one another (Bauer, 2020; Campos et al., 2022; Huang et al., 2017; Xie et al., 2008). Mapping the extent of invasive alien plant populations and their rate of spread has garnered academic interest over time (Pyšek et al. 2020; Bekele et al. 2022, Huang & Asner, 2009). Some studies have also demonstrated which environmental conditions certain invasive alien plant taxa thrive in as well as explain dispersal mechanisms (Halmy et al., 2019; Ndlovu et al., 2018; Xue et al., 2020). Others have explored the interaction between invasive alien plants and land use (Rai & Singh, 2020; Lagabrielle et al., 2010).

2.1.2. Plant traits and the electromagnetic spectrum

Some remote sensing products are inexpensive or free, creating opportunities for under resourced nations (Turner et al. 2015). Moreover, free cloud computing platforms such as Google Earth Engine reduce barriers for data processing for developing nations (Rebelo et al., 2021; Singh et al., 2020), allowing for near real-time mapping of invasions (Rebelo et al., 2021; Rocchini et al., 2018), overcoming challenges associated with traditional approaches (Peerbhay et al., 2016). Certain parts of the electromagnetic spectrum are better for discrimination of plant species, and the red edge and near-infrared portions of the electromagnetic spectrum are particularly useful (Royimani et al., 2019). These parts of the spectrum are sensitive to differences in biophysical and biochemical properties of the plants, for example pigments (~350-700 nm) (Royimani et al. 2019). Other examples of traits which influence the reflectance signatures of plants include nitrogen, polyphenols and lignin (~ 350–3500 nm) (Asner and Martin 2016), as well as water content (1125-2500 nm) (Yilmaz et al. 2008). Additionally, invasive alien plants can further be distinguished from native plant populations as they form dense homogenous thickets that also allow for easier uniform-pixel processing as opposed to mixed species giving off a mixed reflectance per pixel (Peerbhay et al., 2016). Phenology is also an important consideration, where woody invasive alien plants are mostly evergreen and so may be easily distinguished from surrounding native vegetation in the dry season (Matongera et al., 2017; Tian et al., 2020).

2.1.3. Trade-offs in various types of resolution in remote sensing

In remote sensing studies there are usually trade-offs between spatial, spectral and temporal resolution in mapping invasive alien plants (Bradley et al., 2014). Temporal resolution refers to the frequency at which the sensor (e.g. satellite) acquires data over a geographical region of interest, whilst spatial resolution refers to the pixel size making up a scene (Xie et al., 2008). Spectral resolution refers to the number and size of the bands spanning the electromagnetic spectrum. Multispectral sensors typically have only a few bands (sections of wavelengths measured), usually about four to twenty (Masemola et al., 2020; Peerbhay et al., 2016; Robinson et al., 2016; Xie et al., 2022), and include sensors such as Landsat, SPOT, IKONOS, and WorldView (Gangat et al., 2020*;* Van Deventer et al., 2022; Xie et al., 2022). Bands are typically wide, ranging from 430–950 nm in thickness and may cover the visible to infrared (including near infrared (0.75–1.4 μm), shortwave infrared (1.4–3 μm), mid-infrared (3–8 μm), longwave infrared (8–15 μm), and far infrared (15–1000 μm) portions of the electromagnetic spectrum (Zhu et al., 2018). Spatial resolution may range from sub-metre to hundreds or thousands of metres and temporal resolution may range from an acquisition frequency of hours to weeks (Bradley et al., 2014).

Hyperspectral sensors typically have many narrow contiguous bands along the electromagnetic spectrum, ranging from around 150 bands to over 450 (Zhu et al., 2018). Hyperspectral satellites such as Hyperion have over 200 bands (~0.4-2.5 μm thickness) at a 30 m spatial resolution, while airborne sensors like AVIRIS may collect over 400 bands at a 5 m spatial resolution. Due to their narrow width and high number, the bands of hyperspectral sensors are generally contiguous and sample the entire visible and infrared portions of the electromagnetic spectrum, i.e. 350–2500 nm (Ustin et al. 2004; He et al. 2011). This makes hyperspectral imagery useful for more nuanced applications, such as species-level applications, or the mapping of plant functional traits (Somers and Asner 2013; Papp et al. 2021; Lassalle et al. 2023). Due to the large amount of data, hyperspectral sensors can overcome saturation issues (Mutanga and Skidmore 2004). However, this comes at a higher cost of acquisition. Money can resolve these trade-offs, e.g. an expensive hyperspectral airborne campaign is able to collect data at high spatial, spectral and temporal resolution, however this is not feasible for resource constrained nations. Therefore, these trade-offs remain an important consideration, and one resolution type may be traded off against another depending on the purpose of the study.

2.1.4. Imagery types and trade-offs in resolution

Landsat is some of the most used imagery, the sensors of which are sun synchronous, i.e. where they orbit the earth in the same fixed position relative to the sun (Xie et al., 2008). The Landsat TM and ETM satellites were launched in 1982 and orbit the earth over 16-day intervals. WorldView-2, a commercial sensor, was launched in 2009, and has a higher temporal resolution, orbiting every 1.1 days. IKONOS on the other hand, launched in 1999, has a revisit rate of 3-5 days, while Quickbird, launched in 2001, has a temporal resolution of 1-3.5 days. SPOT and MODIS have a much coarser temporal resolution (e.g. weeks). SPOT and MODIS satellites may have poor temporal resolution but they have a swath width that is three to a hundred times larger than that of the IKONOS and Quickbird satellites for example (Bradley, 2014; Zhu et al., 2018; Xie et al., 2008). Other than the advancements of sensors aboard spaceborne satellites, unmanned aerial vehicles

(UAVs) are an upcoming remote sensing technology that can acquire images in a variety of spectral and spatial resolutions and as frequently as needed due to the low cost (Royimani et al. 2019). However, UAVs may be restricted by climatic conditions and campaigns may be impeded by limited battery capacity (Hackney and Clayton 2015). Aerial photographs, a more traditional remote sensing approach, have limited temporal resolution when compared to satellites or UAVs, where the revisit frequency may be a matter of years. However aerial photography may have a long record in countries where campaigns were initiated, and therefore are often useful in long-term vegetation studies, despite their inherent limited spectral resolution (Bradley et al., 2014).

2.1.5. The utility of vegetation indices in mapping invasive alien plants

The use of the appropriate sensor for a given study is essential, however there are also other important considerations. The choice of classifier, indices and the use of approaches such as data fusion can influence results (Rebelo et al., 2021). Vegetation indices for example, have been used extensively in detection of invasive alien plants (Xue & Su, 2017, Pettorelli et al. 2014). The normalised difference vegetation index (NDVI), a measure of plant “greenness” has proven to be useful in vegetation discrimination, and has shown to be related not only to canopy structure but also to photosynthetic activity of the plants canopy (Xue & Su, 2017). In detection of *Pteridium aquilinum* at Cathedral Peak, in the Drakensberg mountains, NDVI applied to Landsat and Worldview imagery improved mapping accuracy (Matongera et al., 2017). The Soil Adjusted Vegetation Index (SAVI) which aims to minimise the soil brightness correction factor when considering the significant effect of soil background on discriminating vegetation types, has been used to map invasive alien plants (Huete 1988). The SAVI index is particularly useful in arid regions where vegetation cover is low, for exampling in mapping *Lantana camara* in the Western Ghats Forest of India (Niphadkar et al., 2017). Other vegetation indices used in discrimination of invasive alien plants include: (i) enhanced vegetation index (EVI) which quantifies vegetation greenness, whilst correcting for atmospheric and other background noise; (ii) visible atmospherically resistant index (VARI) which is used to estimate the fraction of vegetation in an image with low sensitivity to atmospheric effects, and (iii) normalized difference moisture index (NDMI) which has been used to determine vegetation water content (Royimani et al., 2019; Taddeo et al., 2019; Xue & Su, 2017).

2.1.6. Data fusion to improve accuracy of invasive alien plant mapping

Data fusion refers to the integration of two or more different remote sensing datasets with complimentary features to strategically overcome certain limitations (Holden et al., 2021; Peerbhay et al., 2016). Data fusion has been used to develop evapotranspiration measures at a fine scale in the Sahel by incorporating two separate micrometeorological datasets to calibrate and validate a model derived from MODIS imagery (Allies et al., 2022). Hyperspectral data (from an AISA Eagle airborne camera), high spatial resolution WorldView-2 and LiDAR data have all been fused to improve detection of *Solanum mauritianum* (Bugweed) in commercial forestry plantations in KwaZulu-Natal, South Africa (Peerbhay et al., 2016). Data fusion resulted in 6-14% higher accuracies compared to using the datasets individually. In another alien mapping study, Sentinel-1, Sentinel-2 and topographic data were fused to improve accuracy of detecting woody invasive alien plants in water towers (Holden et al. 2021). In some cases, data fusion does not improve accuracy of invasive alien plant mapping (Rajah et al. 2020). For example, Sentinel-1 and Sentinel-2 data were fused with landform data in another study in grasslands, aiming to detect invasive alien plants such as pine, Bugweed, gum, and wattle. It was found that data fusion failed to improve the accuracy relative to Sentinel-2 alone (Rebelo et al., 2021).

2.1.7. Advances in machine learning for classification algorithms

A classifier is an algorithm that sorts data into one or more sets of classes (Xie et al., 2008) and may be either parametric or non-parametric (Royimani et al., 2019). Parametric classifiers assume that the chosen dataset for training the classification process represents 100% cover of the feature for a given pixel. This works well for homogenous landscapes such as forestry plantations or monoculture farming. Parametric image classifiers provide classification output at a pixel level and that significantly compromises the classification accuracy, especially with coarse to medium spatial resolution multispectral datasets. The major problem arising from this is that precision becomes limited in heterogenous landscapes due to mixed pixels (Matongera, 2016). An example of a parametric classifier is Mahalanobis Distance, which employs multivariate generalization where standard deviations from a given point is quantified from the mean of multivariate distribution and accounts for how correlated the variables are to one another. Maximum likelihood is another example of a parametric classifier and involves determination of the parameters of an assumed probability distribution, with the input of observed data. The effectiveness of different parametric and nonparametric classifiers used for invasive alien plant detection using IKONOS imagery was tested, and it was found that the Maximum Likelihood classifier achieved over 75% accuracy which was comparable to that of the best performing nonparametric classifier (Gil et al., 2011). However, when considering large, complex datasets, a parametric approach for image classification may not be sufficient to derive maximum benefits of categorizing feature classes (Niphadkar et al., 2017). For example, a pixel and object based parametric (maximum likelihood) classification was found to yield low (~60%) accuracy in detecting *Lantana camara* in a tropical forest.

Non-parametric classifiers, on the other hand, sub-divide individual pixel data to increase the spectral variance of different features for an improved classification accuracy. These classifiers are thought to have refined capabilities to retrieve biophysical features in vegetation when compared to the linear parametric classifiers (Royimani et al., 2019). The most widely used nonparametric classifiers in invasive alien plant remote sensing include Support Vector Machine (SVM), random forest (RF), and Artificial Neural Networks (ANN). Support Vector Machine is an unsupervised model which is comprised of a learning algorithm that aims to create the most appropriate decision boundary line between classes, referred to as the hyperplane that segregates n-dimensional space. Invasive alien plants have been discriminated with over 75% accuracy using Support Vector Machine, with 10% higher accuracy than a parametric classifier, Mahalanobis Distance (Gil et al., 2011). More recent studies such as Holden et al., (2021); and Rebelo et al., (2021), have also utilized Support Vector Machine for mapping woody invasive alien plants in important catchment areas with over 90% accuracy.

Random Forest has also been used for distinguishing invasive alien plants and consists of many decision trees based on the data, which are used to obtain an average to improve accuracy over a single-tree approach. It is based on the concept of ensemble learning which is a process of combining multiple classifiers to solve complex problems and improve model performance. In one study, morphologically similar woody plants in a savanna were discriminated with an accuracy of approximately 65% when using multispectral sensors combined with Random Forest (Fundisi et al., 2022). This may not seem to be high accuracy, but given that the trees were morphologically similar and inhabiting a heterogenous environment, it is a strong performance. Many other studies have achieved high levels of accuracy in discriminating invasive alien plants from other vegetation classes with using the Random Forest classifier (Peerbhay, et al., 2016; Saranya et al., 2021; Singh et al., 2021). The Artificial Neural Network is another effective model which incorporates the computational process that simulates the human–brain. It is a useful tool for modelling complex ecosystems because it is able to predict how ecosystems respond to changes in the environment. In addition, Artificial Neural Networks can be used to discover relationships among environmental variables, which aids in the understanding of ecosystem function. A study attempting to map one of the most common invasive alien plants in Europe, Common Milkweed, tested both Support Vector Machine and Artificial Neural Network accuracies from a UAV with a hyperspectral sensor (Papp et al. 2021). The accuracies were high for both classifiers (92.95% and 99.61% respectively).

2.1.8. Prospects for remote sensing invasive alien plants

One challenge includes the low accuracy achieved in discriminating invasive alien plants in cases of mixed pixels. Algorithms can only easily identify different feature classes if their spectral profiles are distinct and match that of the training data. If pixels are too large (e.g. coarse spatial datasets), the discrimination of vegetation types may be challenging. This is particularly difficult in heterogeneous landscapes. This issue can be somewhat overcome by using data with higher spatial resolution (Rebelo et al., 2021; Waśniewski et al., 2022) or data fusion (Pettorelli et al. 2014). Disturbances such as fire or land-cover change present challenges in mapping invasive alien plants, however exploiting time series data can aid in accounting for these variables (Matongera et al., 2017; Moncrieff, 2022; Moncrieff et al., 2021; Slingsby et al., 2020). Cost may also be a challenge, however there is also a large amount of free satellite imagery and even open source software and cloud computing, such as Google Earth Engine. Recent invasive alien plant remote sensing studies have made use of these freely available datasets and software, producing reproducible and transparent methodologies (Holden et al., 2021; Moncrieff, 2021, 2022; Rebelo et al., 2021; Slingsby et al., 2020).

Remote sensing shows great promise for mapping invasive alien plant taxa in various settings. Understanding invasive alien plant distribution is important, but understanding invasive alien plant impacts is also fundamental. Some studies have done so, for example, the severity of wildfire in Knysna was related to invasive alien plant biomass using remote sensing (Kraaij et al. 2018). Other studies have quantified the impacts of invasive alien trees on water using remote sensing (Moncrieff et al., 2021; Rebelo, et al., 2022). The socioecological impacts of invasive alien plants on poorer households in South Africa have also been studied (Reynolds et al., 2020).

2.2. Invasive alien plant density and biomass

2.2.1. Invasive alien plant density

Density-dependant impact studies of invasive alien plants have been undertaken to understand how the density of an invasive alien plant population can relate to the potential of its impacts (Pawson et al. 2010; White and Shurin 2011). The density of alien plant invasions is related to the potential severity of impacts (Pawson et al. 2010). For example, high densities of *Robinia pseudoacacia* in floodplain forests have been shown to severely impact soil health (Staska et al. 2014), while other species like *Heracleum mantegazzianum* and *Sargassum muticum* have been shown to displace more native vegetation at higher densities (Thiele et al. 2010; White and Shurin 2011). Increases in invasive alien plant density has also been shown to significantly decrease heterogeneity in the landscape, with knock-on effects on the ecosystem (Le Maitre et al., 2011; Naudé, 2012; Rebelo et al., 2019; Tererai et al., 2013). Furthermore, higher densities of invasive alien plants such as gums, pine, and wattle (i.e. *Acacia dealbata, A. saligna,* and *A. longifolia*) has been shown to increase fire-risk (Le Maitre et al. 2011; Kraaij et al. 2018). The density of alien plant invasions also affects management methods, including labour, chemicals and equipment (Cheney et al. 2020, de Lange et al., 2022; Marais et al., 2004; van Wilgen et al., 1997), with implications for budget (de Lange et al. 2022). The density of vegetation can be measured in many ways; one such metric includes fractional woody cover, which can be estimated from relative greenness (e.g. NDVI) (Arroyo et al. 2010; Naidoo et al. 2012; Naidoo et al. 2015; Urbazaev et al. 2015; Wessels et al. 2019; Vermeulen et al. 2021). Another metric of density is above ground biomass which is measured in tonnes per hectare; a valuable measure for products such as firewood, fuel wood for electricity, biochar, and activated carbon for the agricultural and pharmaceutical sectors (Askne et al., 2017; Brovkina et al., 2017; Kachamba et al., 2016; Kozak et al., 2023; Li et al., 2021; Petersen et al., 2022; Stafford et al., 2017).

2.2.2. Invasive alien plant biomass

There have been several biomass studies done on commercial forestry related taxa, but less so for woody invasive alien plants (Boudreau et al. 2008; Goetz and Dubayah 2011; Dube et al. 2014; Bulut 2023). Biomass determinations are fundamental for forestry and agriculture studies as they are a measure of yield (Cao et al. 2019; Jin et al. 2020; Bulut 2023). Greater biomass of woody invasive alien plant populations leads to higher consumption of water (Le Maitre et al., 2020). Biomass determinations of invasive alien plants are gaining interest to support private sector investment into clearing efforts via value added industry (Stafford & Blignaut, 2017; Stafford et al., 2018; Vera et al., 2022; Wise et al., 2012). Being able to quantify and map the biomass of woody invasive alien plants could therefore be valuable to support value added industry funding alien tree clearing (Peerbhay et al., 2016). Typically biomass studies of woody invasive alien plants in South Africa have been at a small scale (Gouws & Shackleton, 2019; Juba, 2020; Stafford & Blignaut, 2017).

2.2.3. Methods for determining biomass of invasive alien plants

Historically biomass studies involved in-field destructive methods which are highly accurate, costly and not widely transferable (Naidoo et al., 2012; Meister et al., 2022). Therefore, there is a need for a different approach to obtain spatial biomass data. This can be achieved using a combination of satellite data and in-field biomass data and allometric equations. Allometric equations are used to calculate biomass based on the relationship between indices such as plant height, diameter at breast height, and canopy radius (Juba 2020, Latella et al. 2022; Hiernaux et al. 2023; Kozak et al. 2023). Remote sensing approaches to estimate biomass have proven successful (Bouvet et al. 2018; Jin et al. 2020; Duncanson et al. 2022; Bulut 2023; Liang et al. 2023). Leaf Area Index, the one-sided green leaf area per unit area ground surface area; has been mapped using remote sensing (Naidoo et al., 2019, 2022; Palmer et al., 2016) and has been found to be well correlated with biomass (R^2 = 0.91) (Jin et al., 2020). Synthetic Aperture Radar (SAR) techniques have also been used to map biomass and can be categorized into different polarizations and frequencies including single frequency (L-band, C-band, or X-band); multiple frequency (a combination of two or more frequency bands); single polarization (VV, HH, or HV); and multiple polarization (a combination of two or more polarizations) (Zhu et al., 2018). Phased Array type L-band SAR is an active microwave sensor using the L-band frequency which can achieve cloud free land observations and as a wavelength of 15-30 cm that is able to penetrate dense vegetation (Zhu et al., 2018). Some studies have fused optical and SAR data to map the differences in above ground biomass of wetlands compared to adjacent drylands with an accuracy of R^2 = 0.63 (Naidoo et al., 2019). An above ground biomass map of African savannas and woodlands has been produced from Advanced Land Observing Satellite-1 (ALOS) PALSAR data at a spatial resolution of 25 m by relating the PALSAR backscatter to biomass with the help of ancillary data such as vegetation attenuation and tree cover (Bouvet et al. 2018).

Besides SAR, another active remote sensing approach includes LiDAR (light detection and ranging) technology. This includes solid-state lasers, liquid lasers, gas lasers, semiconductor lasers, and chemical lasers (Zhu et al., 2018). LiDAR-based products such as Digital Elevation Model (DEM) and Canopy Height Model (CHM) can be developed with high levels of accuracy if the data are of a sufficient resolution (points per square meter). Airborne LiDAR is expensive to obtain and therefore is usually not acquired over large areas (Urbazaev et al. 2015). Many studies have successfully estimated invasive alien plant biomass with airborne LiDAR sensors (Jansen et al., 2019; Latella et al., 2022; Mathieu et al., 2018; Meister et al., 2022). More recently, spaceborne LiDAR technologies such as Global Ecosystems Dynamics Investigation (GEDI), mounted on the International Space Station have been used. The GEDI sensor has been used in several studies to determine canopy height and vertical structure in the landscape and subsequently biomass (Duncanson et al., 2022; Li et al., 2023; Liang et al., 2023).

2.2.4. Remote sensing and allometry for quantification of invasive alien plant biomass

The integration of allometric relationships and LiDAR data hold potential in determining woody invasive alien plant biomass. This has been done for certain crops and savanna woody species (Naidoo et al., 2012, 2022; Meister et al., 2022; van Wilgen et al., 2022). The accuracy of woody above ground biomass in South African savannas using a combination of X-band (TerraSAR-X), C-band (RADARSAT-2) and L-band (ALOS PALSAR) radar datasets was quantified (Naidoo et al., 2015). Training and validation data were derived from airborne LiDAR data. The L-band SAR frequency performed best (R^2 = 0.78). Large footprint LiDAR waveform measurements were used in a waveform profile-weighted height-based allometric equation to determine biomass (Meister et al., 2022). The allometric equation included relationships between tree height with stem diameter and crown volume with tree height, which were significant (R^2 = 0.70–0.79, RMSE = 42–754 m^3). Allometric relationships have also been developed between crown area or canopy cover and tree height and integrated into LiDAR (i.e. without the need for a diameter measure), which is novel and has significant applicability for biomass determinations of invasive alien plants (Naidoo et al. 2015; Hiernaux et al. 2023). There are considerable field invasive alien plant biomass datasets and established allometric relationships (Holden et al., 2021; Juba, 2020; Kotzé et al., 2025; Peerbhay et al., 2016), but these have not yet been integrated with remote sensing to develop detailed biomass maps of invasive alien plants.

2.3. Water use impacts of invasive alien plants

2.3.1. State of the art for South Africa

Woody alien plants are well known for consuming significantly more water than the native vegetation they invade (Le Maitre et al., 2000, 2015, 2016; Moncrieff et al., 2021). The potential impact of invasive alien plants on water at a national scale has been shown to be serious and a national programme to manage these species was declared to be essential to protect water resources (Le Maitre et al., 2000). Woody invasive alien plants, particularly gums, wattle and pine, have been found to reduce runoff by 2.9% of the naturalized mean relative to native vegetation (Le Maitre et al. 2016). Wattles (*Acacia mearnsii, A. dealbata, A. decurrens*) are estimated to have the greatest impact on streamflow reduction (34%), followed by pines (19.3%) and gums (15.8%) (Le Maitre et al. 2016). Economic consequences of having to clear fully invaded catchments run into the millions of USD (Maitre et al. 2002). Red River Gum, *E. camaldulensis* (large trees of about 50 cm diameter), were found to consume up to 260 litres of water a day in hot and dry weather (Dzikiti et al., 2016).

Evapotranspiration is the largest and one of the most fundamental components of the hydrological cycle in terms of water-use, and can be defined as the transfer of water to the atmosphere from plants and surfaces in the form of water vapour (Fisher et al. 2011). In South Africa, studies have shown that evapotranspiration can exceed rainfall in various biome types where woody invasive alien plants are present (Dzikiti et al. 2019). This means that the rainfall in the area is at a deficit and that fresh water sources in the landscape, e.g. aquifers, are diminishing over time. One study showed that evapotranspiration exceeded rainfall for three consecutive years due to woody bush encroachment including *Colophospermum mopane* growing within a semi-arid savanna (Aldworth et al., 2023). Similarly, during years of lower rainfall, evapotranspiration was found to exceed rainfall in grasslands especially in instances where there was encroachment of woody vegetation in the study area (Gwate 2018). Another study found that evapotranspiration exceeded rainfall by 7% in the Albany Thicket, and this suggested that the Albany Thicket was supported by ground water supplies (Palmer et al., 2020). Evapotranspiration estimates from two remote sensing products, one based on the Surface Energy Balance Algorithm for Land (SEBAL) model and the other using a dual source Penman–Monteith model, showed that up to 2.0±0.3 ML of water can potentially be saved per year for each condensed hectare of Eucalyptus population that is cleared (Everard 2020).

2.3.2. Different methods to measure plant water use

Different measurement approaches have been used to determine water use and better understand how invasive alien plants interact with water in different environmental conditions. Assessing the evapotranspiration rates of certain vegetation types including invasive alien plants is a reputable way to measure water use across a given landscape (Aldworth et al., 2022; Dzikiti et al., 2019; Gray et al., 2022; Gwate et al., 2018; Palmer et al., 2023). Evapotranspiration is considered a key ecosystem level measure of water use, besides more in situ level measurements such as sap flow and lysimetry which are at the plant level. Sap flow measurements include an instrumentation technique whereby sensors are placed into the plant's tissues including the xylem to measure temperature differences that indicate sap flow information and lysimetry refers to tanks or containers, that define a specific boundary that contains soil water and facilitates the measurement of either the soil water balance or the volume of water percolating vertically.

2.3.3. Modelling water use with evapotranspiration measurements and remote sensing techniques

A variety of modelling approaches have been used in combination with remote sensing to estimate the evapotranspiration of invasive alien plants. This can be done through both direct and indirect methods (Verstraeten et al. 2008; Wang and Dickinson 2012). Direct methods include the eddy covariance flux towers which acquire turbulent flux data by calculating the covariance of fluctuations (Rana and Katerji 2000). Scintillometers and surface renewal systems on the other hand are indirect measures. Scintillometers measure changes in the refractive index of air are used to derive turbulence statistics (McAneney et al. 1995). This is done using a transmitted beam of light between a transmitter and a receiver where the fluctuation in light intensity is analysed. Indirect measures typically make use of the energy balance, where evapotranspiration is calculated from the difference between net radiation and the heat flux (Ershadi et al. 2011). Surface renewal is a method which uses high-frequency air temperature measurements to determine sensible heat flux (H), and soil probes to measure the ground heat flux (G), and together with data on net solar radiation solves the energy balance equation to estimate evapotranspiration (ET) (Gray et al. 2021).Other indirect measures include relative humidity and sensible heat flux which have been used effectively in discriminating water use of different vegetation types (Gray et al., 2021; Palmer et al., 2023).

There are many different remote sensing evapotranspiration products available (over 30; see Cogill et al. 2025), including MOD16, which is part of NASA/EOS project (1-km^2 spatial resolution and covers 109 million km^2 of global vegetated land areas at 8-day, monthly and annual intervals using the Penman-Monteith equation (Running et al. 2019). These different remotely sensed products are based on various models, some of the key ones which include Penman-Monteith and Priestly-Taylor amongst others. Penman-Monteith model is a biophysical model which assumes that actual evapotranspiration is a combination of canopy transpiration (Ec), evaporation of intercepted water by canopy and litter (Ei), and soil evaporation (Es). The Priestly-Taylor is a simplification of the Penman-Monteith equation and has been used to allow calculations of evapotranspiration under conditions where soil water supply limits evapotranspiration (Shuttleworth & Calder, 1979). Other remote sensing products include proprietary models such as SEBAL ("surface energy balance algorithm for land”), an image processing model which computes a complete radiation and energy balance and takes parameters such as vegetation indices, surface albedo, surface temperature, and momentum flux into consideration for each pixel (Ndou et al., 2018; Sun et al., 2011).

High-quality evapotranspiration data are available in South Africa for specific locales (Gray et al., 2022; Gwate et al., 2018; Palmer et al., 2023; Palmer et al., 2015, 2020; Preston et al., 2018), but there is not much integration of these datasets to study patterns within the region. Neither has there yet been an attempt to aggregate these datasets and couple them with remotely sensing products to explore evapotranspiration impacts spatially and at scale. Furthermore, there is very little information on relative water-use, compared to native vegetation evapotranspiration for example. One study did quantify the water use impacts using flow reduction factors of many invasive alien plant taxa including Australian acacias, *Cereus jamacaru, Eucalyptus sp., Pinus sp., Opuntia sp.* relative to native taxa (Le Maitre et al., 2015, 2016). This approach involves including information on growth rate, growing conditions, age, density and location. Quantifying water use is a significant part of understanding invasive alien plant impacts in South Africa, which is a water scarce country facing increasing demand for fresh water resources (Hedden and Cilliers 2014).

2.4. Conclusion

Invasive alien plants are an ever-growing problem, and their associated impacts are becoming increasingly serious and costly (Pyšek et al., 2020; van Wilgen et al., 2022). This is exacerbated with anthropogenic climate change that favours woody species over grasses (Early et al. 2016; Hulme 2017; Liu et al. 2017; Pyšek et al. 2020). Remote sensing can be an effective and inexpensive tool to not only detect populations of targeted invasive alien plants, but also better understand their impacts (Royimani et al., 2019). With access to freely available products and platforms, we can become more strategic in our approach of effective invasive alien plant management. These tools can help us to strategically manage woody invasive alien plants for the long term in a water scarce developing country.

3. METHODS

3.1. Site selection

Given that it was not within the scope of this project to map invasive alien plants in the entire country, the proposition was to select study sites within selected surface water strategic water source areas (SWSAs). Potential study sites were brainstormed at a project team workshop and at the inaugural Water Research Commission project reference group meeting, resulting in nine suggested study catchments (**Figure 1**). The final selection of sites was based on four criteria:

1. **Water security** – catchments within surface water strategic water source areas which sustain water supply schemes for both urban/industrial and irrigation purposes, which experience, or are likely to experience, poor water security.
2. **Impacts of invasive alien plants** –surface water strategic water source areas experiencing the greatest estimated reductions in mean annual runoff due to invading alien plants.
3. **Spatial variation** – selected study sites should capture bioclimatic variation.
4. **Data scarcity** – catchments that are data scarce or under-researched.

Based on these criteria, four study site catchments were selected.

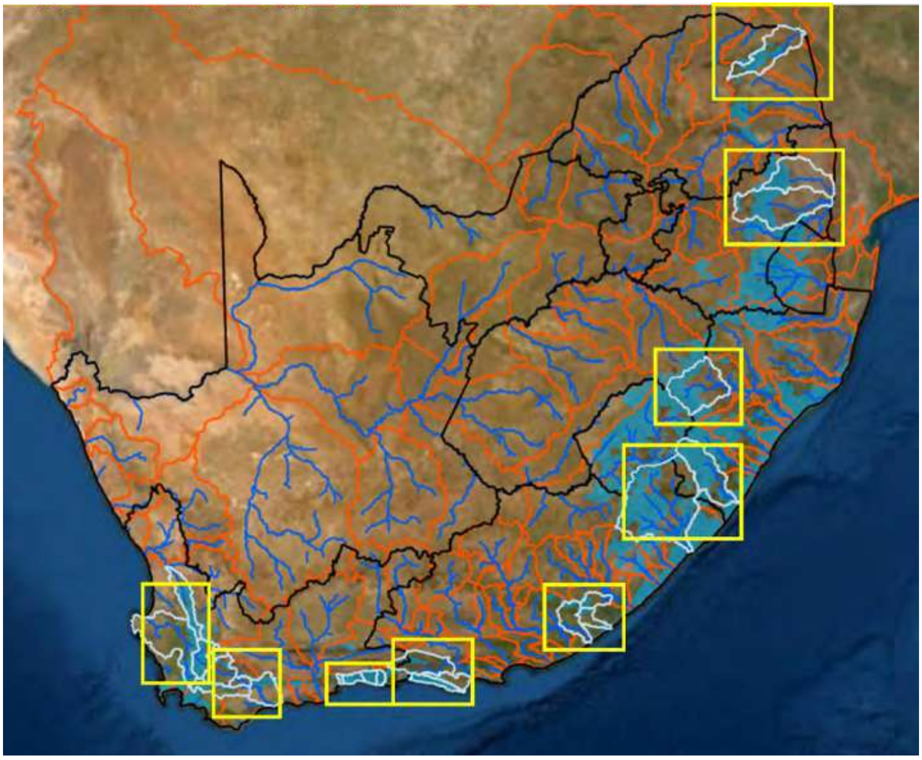


Figure 1. *The originally proposed study sites for the MAPWAPS project.*

3.2. Woody invasive alien plant occurrence

The methods developed by Holden & Rebelo et al. (2021) were applied in this study and tested further in different biomes and climate regions (**Figure 2**). Starting with stakeholder engagements (3.2.1) to determine invasive alien taxa of importance, fieldwork was then planned and conducted (3.2.2), and datasets were processed and finalized (3.2.3). Classifications were then performed (3.2.4), and validation (3.2.5) and ground truthing done (3.2.6). Dates of all activities, including stakeholder engagements, fieldtrips and ground truthing trips are recorded in **Table 1**. Ethics approval was granted through Stellenbosch University (ethics approval numbers: FESCAGRI-2022-26880; FESCAGRI-2022-26881).

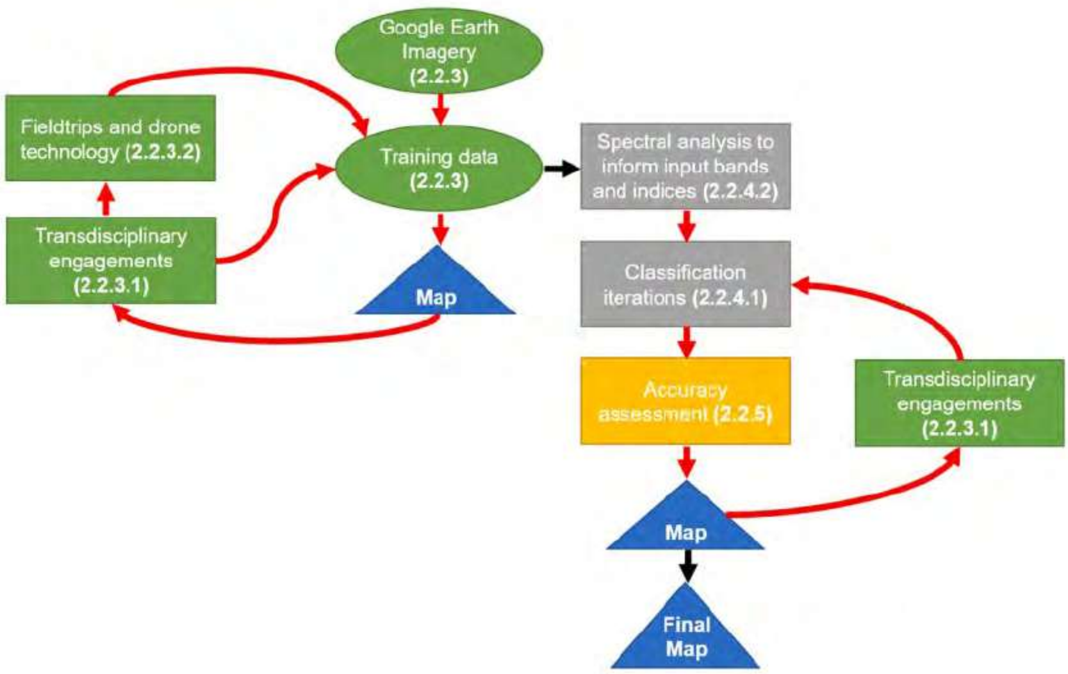


Figure 2. *The workflow of the alien mapping methods, from Holden & Rebelo et al. 2021.*

Table 1. *Dates of the stakeholder engagements, fieldwork and ground truthing per catchment.*

Catchment	Workshop	Fieldwork	Ground truthing
Luvuvhu	2 March 2023	18 – 30 July 2023	1 – 4 July 2024
Sabie-Croc	28 February 2023	31 July – 14 August 2023	5 – 10 July 2024
Tugela	16 February 2023	16 – 27 October 2023	11 – 12; 19 – 21 July 2024; 28 February 2025; 1 March 2025
uMzimvubu	22 February 2023	19 May – 6 June 2023	13 – 14 June 2024; 19-21 February 2025

3.2.1. Stakeholder engagements

We held stakeholder workshops for each study catchment to determine the most important woody invasive alien plant taxa of concern from relevant researchers and practitioners that are involved in ecological and/or invasive alien plant projects in each of the catchments. The format was online for all sites, except for the uMzimvubu Catchment. For the uMzimvubu, the uMzimvubu Catchment Partnership (UCP) meets quarterly, and we were able to run our workshop physically at one of these meetings in 2023. During these workshops, the purpose and scope of the project was presented, and then small breakaway groups brainstormed key invasive alien plants of concern. Once the small groups rejoined the plenary, we held a prioritization exercise where these taxa were ranked, and the top four or five taxa selected. Additional practical questions were asked of stakeholders, to prepare for subsequent fieldwork. Based on these results, a list of land-use/land-cover classes were prepared for each catchment, including four to five woody invasive alien plant taxa.

3.2.2. Fieldwork

Approximately two weeks were spent in each catchment, collecting training data for each land-use/land-cover class in the form of geotagged photos using the South African road network. Based on the limitations of the freely available cloud computing platform (Google Earth Engine), the limit of points one can process is about 5000. For approximately 15 classes, this would be approximately 300 points per class. We tried our best to keep these classes even as much as possible when collecting training data to avoid bias. Invasive alien taxa were identified using field guides where taxon was not known. In some cases, e.g. in the uMzimvubu where it was a stakeholder request to discriminate between Black and Silver Wattle, which are morphologically highly similar, leaf traits (like jugary glands, leaf shape, and colour) were used for identification. However Black and Green Wattle were much harder to tell apart, even with traits, and therefore for this study, we grouped Black and Green Wattle into one class, and Silver Wattle into another. In addition to the geotagged photo, metadata were also collected. The platform used to collect data in the field, was Cybertracker. Cybertracker was used as it had good stability in remote places relative to iNaturalist. The data collection protocol used in this project and developed as part of the BioSCape Invasive Alien Tree Mapping Working Group can be accessed via this link. What is extremely important is the “pure pixel approach” applied in this study (**Figure 3**). Every training point collected is collected only from pure pixels of the target class, and this means that a pixel of 10x10 m can be collected from the imagery such that it only contains the target class and nothing else. Mixed pixels result in confusion of the machine learning algorithm and less accurate results.

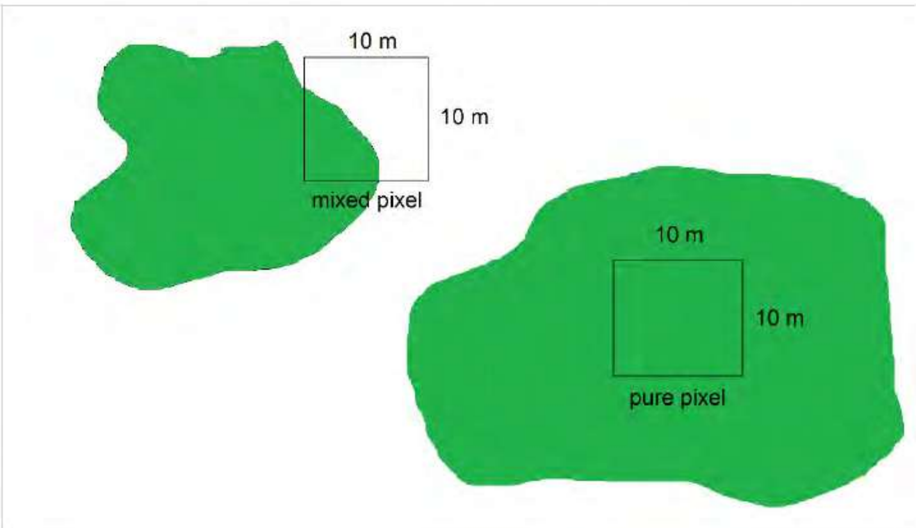


Figure 3. *An illustration of the pure pixel approach used in this study.*

The following metadata were collected:

i. The name of the land-use/land-cover class captured in the photograph
ii. The direction of the land-use/land-cover class from the photographer
iii. The distance to the class of observation

iv. The Global Positioning System (GPS) identification number (additional coordinates were collected from a GPS as a back-up)
v. An estimate of the density (percentage cover) of the invasive alien plant stand
vi. An estimate of the height of the invasive alien plant stand (i.e. to try and relate to age)

3.2.3. Datasets

During the fieldwork, each afternoon, the collected training data were processed, using the distance and direction data collected, such that the point was relocated from the road, to the stand that was being observed. To do this, geotagged photos were imported from cell phones into ArcGIS Pro, using the "geotagged photos to points" tool. Each photo is then assigned to a point, using the GPS coordinates derived from the cell phones. Where coordinates were incorrect, the coordinates from the hand-held GPS device were used instead. These points were then joined to the metadata downloaded from the Cybertracker project using the Photo ID recorded and a "join" function in ArcGIS Pro. Once the data were curated, then point harvesting took place. This is where some stands might be extremely large, but in the field only one point would be captured. To increase sampling of the variation within large stands, additional points were harvested using a desktop approach, comprised of the Sentinel-2 basemap that matched the date of the fieldwork. Once the final classes approximated 300 points, or as close as possible, the final shapefile was then loaded into Google Earth Engine as an asset in preparation for classification.

All of the photos have also been uploaded for perpetuity, joined with all their metadata, on iNaturalist in the specifically designed project: https://www.inaturalist.org/projects/mapwaps. There is an embargo of one year, but following this, the data will be available to anyone. These data also interface with the Global Biodiversity Information Facility, and therefore our photographic dataset has contributed to international databases. In addition, the training data and classification maps for each of the study catchments have been archived on SUN Scholar, with persistent links. There is also currently an embargo for a year, but this will lift in due course and the data will be publicly available:
Tugela Catchment: https://doi.org/10.25413/sun.25066151
uMzimvubu Catchment: https://doi.org/10.25413/sun.25050401
Luvuvhu Catchment: https://doi.org/10.25413/sun.25050314
Sabie-Crocodile Catchment: https://doi.org/10.25413/sun.25050368

3.2.4. Classification approach

Classifications were done using the training data sets, after setting aside 30% of the data (30% per class) for each catchment. Ten of the thirteen Sentinel-2 bands were used, and 39 indices (**Table S1**). Different combinations of classes were tested, as well as different numbers of samples for classes where pure pixels were limited, to see what produced the most accurate invasive alien plant map (**Table S2**). In addition, different classifiers were explored, including Support Vector Machine, Random Forest and Gradient Tree Boost (**Table 2**). We found that Random Forest consistently outperformed the other classifiers and therefore we proceeded with this classifier for this project (**Table S2**).

Table 2. The six classifications run for each of the four catchments and their specifications.

#	Name	Description	
		Classifier	**Features**
1	SVM S2	Support Vector Machine	All Sentinel-2 bands + indices
2	SVM S2 + S1	Support Vector Machine	All Sentinel-2 bands + indices fused with Sentinel-1
3	SVM S2 + ALOS	Support Vector Machine	All Sentinel-2 bands + indices fused with ALOS landform and elevation dataset
4	SVM All	Support Vector Machine	All Sentinel-2 bands + indices fused with Sentinel-1 and ALOS landform and elevation dataset
5	RF	Random Forest	The best from classification 1-4
6	GTB	Gradient Tree Boost	The best from classification 1-4

3.2.5. Validation

An accuracy assessment was conducted using the reserved 30% of the training data for each catchment. Three types of accuracy were recorded: (1) Overall" is the accuracy for all classes of the map (n=15-18), (2) "IAP Accuracy" refers to the alien classes combined, compared with all other classes combined (n=2), and (3) "Intra IAP Accuracy" is the accuracy for the invasive alien plant classes only (n=5).

3.2.6. Ground truthing

Once the maps were produced, an independent ground truthing exercise was conducted, for dates see **Table 1**. As opposed to validation which is pixel based, this follows a polygon approach, whereby polygons of stands of invasive alien trees were recorded, and then verified on the maps. This is evaluated by calculating the number of correctly classified pixels within each polygon. Typically this approach is far more robust, but yields lower accuracies relative to validation.

3.2.7. Comparison with NIAPS

During the third year of this project, the National Invasive Alien Plant Survey (NIAPS) was released. It therefore makes sense to compare outputs. However at the date of writing this report, the full methods of NIAPS were not yet released and therefore there may potentially be some misinterpretations, as the full details of the methods have not been disclosed. One key difference between this project and NIAPS is that this project does not discriminate between invasions and plantations, whereas NIAPS only maps invasions and excludes plantations. How plantations are defined, and whether this includes woodlots, is unknown. For visualization, alien density between 20-100% was mapped, and between 0-20% was excluded. For calculations of area invaded (km^2), everything (i.e. 0-100%) was included.

3.2.8. Other analyses

To determine the relative areas of invasions (km^2) as opposed to plantations, we used the National Land Cover dataset (2022) to extract the three plantation classes. These classes were merged into one, and clipped to our study catchments. This layer was intersected with our woody invasive alien plant maps to recalculate area and percentage invaded with the plantations masked.

3.3. Woody invasive alien plant density

The aim of this section was to test a simple approach to estimate woody invasive alien plant density (percentage cover) for viability. We ended up testing three potential indicators of density. (1) We calculated the probability of invasion for each pixel for each woody invasive alien plant taxon, using the Random Forest classifier. We then related this layer to the presence of these taxa based on the alien map (3.2). Using zonal statistics we then extracted the mean probability per 10 m pixel, as a proxy for density (percentage cover). The logic is that in high density invasions, there would be a high probability of invasion at the pixel level, and vice versa for low density invasions. There are instances where this logic breaks down, but in general it could be a useful indicator to test. The results were sense-checked using field collected estimates of density for a few examples. (2) We also calculated the number of points of each alien class within 100 m by 100 m grid cells with the assumption that in cases with many pixels of a certain alien class, this would relate to high density (percentage cover). (3) Lastly we tested the Normalized Difference Vegetation Index (NDVI) calculated from Sentinel-2 imagery as a proxy for density (percentage cover). Accuracy was tested with a small set of field-collected density data.

3.4. Woody invasive alien plant age

The aim of this section was to test a simple approach to estimate woody invasive alien plant age for viability. We used the MODIS Burned Area Monthly Global 500 m dataset in Google Earth Engine (MCD64A1.061) to calculate vegetation age based on the Julian date of the fire extracted from the metadata between 2000 to 2024. Vegetation age (in years) was converted from the Julian calendar date and the year of the most recent fire for each pixel. This layer was then exported as a raster, and intersected with the invasive alien tree map for each catchment, and the average age of each invasive alien plant taxon calculated. A sense check was performed, by converting the height of invasive alien tree stands to age (years) based on forestry expert opinion. In some cases, it is possible that this layer would not be appropriate to use to derive vegetation age, as there may have been a fire in a pixel that only burned the grasses and not the tree component. This is especially relevant in grassland/savanna ecosystems where fires may be cooler than for shrublands, and not all above ground vegetation is incinerated (i.e. fires pass beneath trees, and therefore the trees may be far older than the time since fire).

3.5. Woody invasive alien plant water-use

Available local in-situ evapotranspiration data were obtained from various organisations and individuals from several types of instrumentation (e.g. eddy covariance flux towers and scintillometers) across South Africa for different land-covers, yielding a flux tower database of 14 stations. These data were processed to obtain the same format and variables, were gap filled (using the SAEON code for patching) and aggregated to a monthly timestep (**Figure 4**). A short-list of remote sensing evapotranspiration products was then made, and the time-series results for each pixel corresponding to the flux tower locations, was extracted and processed in the same way. These two-time series (field observed, and satellite observed) were then related to each other, and various performance metrics used to evaluate accuracy. This includes overall, interannual and seasonal performance assessed with metrics such as R^2, PBIAS, KGE. The best evapotranspiration products were then used to produce an ensemble model output, the performance of which was also tested (**Figure 4**). This ensemble model was then run for each catchment, and mean water-use per taxon was extracted using the invasive alien plant maps produced in this project (3.2). This is a major innovation for this project, as most other studies use only one product (Van Niekerk et al. 2023), which our research shows may perform well in some bioclimates, but not others. No one product emerged as best overall. For a more detailed description of the methods, please refer to (Cogill et al. 2025).

Relative water-use among different vegetation classes was then compared, for example among classes using heatmaps. The water-use statistics of each vegetation class was done via ArcGIS Pro using the "*Zonal Statistics to Table*" function. This relative water-use was then compared inside and outside of the surface water strategic water source areas considered in this study. The relative water-use was also calculated as potential volumes of water savings at a catchment scale based on the area of invasion of each taxon (km^2), after excluding plantations based on the plantations delineated in the 2022 National Landcover Map. A review of the literature in terms of the evapotranspiration of various vegetation classes was performed, and the annual evapotranspiration, location and taxon of interest was included, and the results were compared to those of this study.

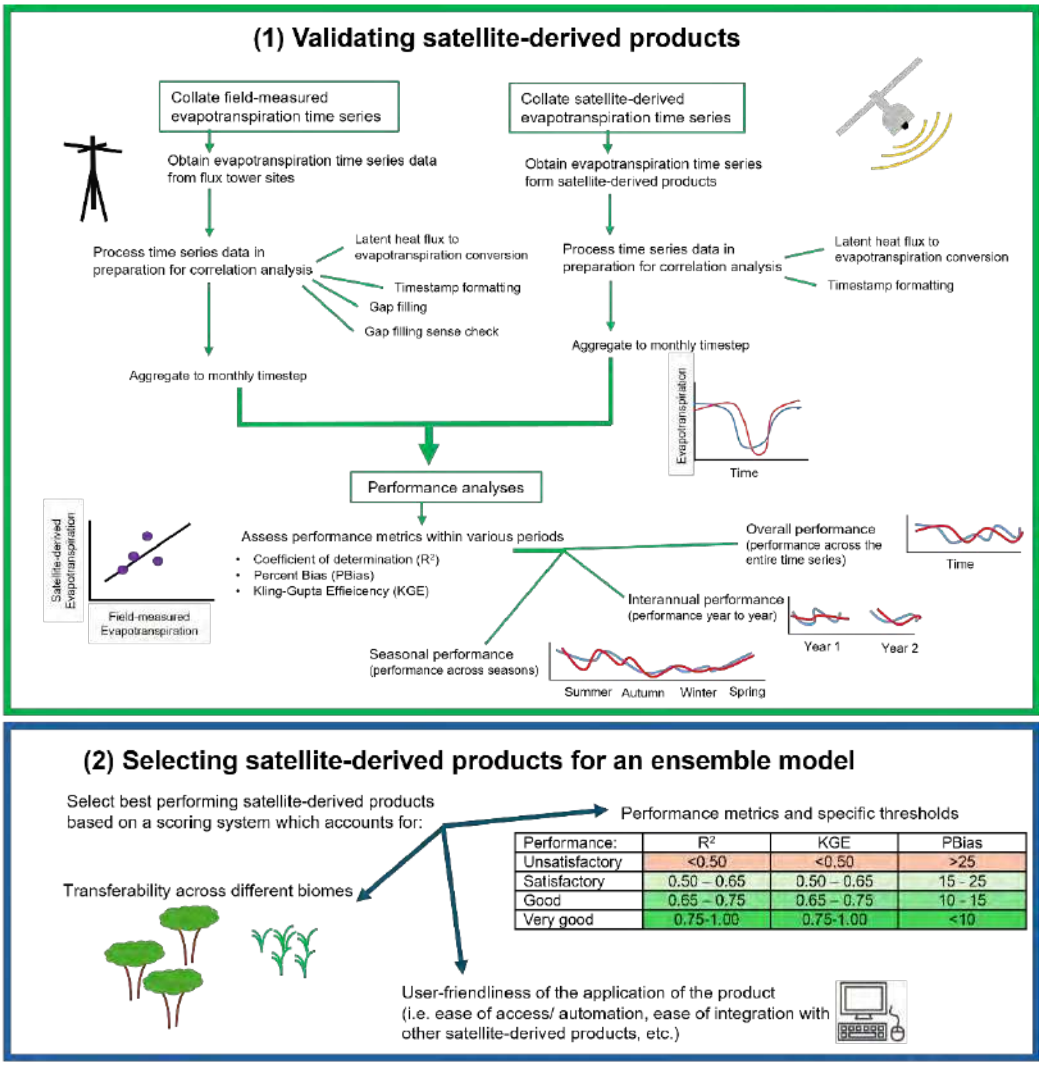


Figure 4. *The workflow for the first part of the water-use component of this project, taken from Cogill et al. 2025.*

3.6. Practical application of dataset for plantation monitoring

To explore the relationship between plantations and invasions of woody alien plants we used the plantations from the 2022 National Land Cover. We extracted all three plantation classes and merged these into one plantation class by reclassifying the raster. The three plantation classes were class 5 (contiguous & dense plantation forest), class 6 (open & sparse plantation forested plantation), and class 7 (temporary unplanted (clear-felled) plantation forest). For the plantation spread analysis, we applied buffers (100, 500, 1000 m) to the plantation boundaries, and calculated the total area of invasion of alien woody plants within these three different buffers adjacent to the plantation, and then calculated the relative area standardized for distance from plantation (e.g. area of invasion per 100 m increment of distance from the plantations). These were then plotted to explore trends. Our hypothesis was that invasion would be higher (i.e. occupy more area) closer to the plantation blocks.

For the plantation compliance analysis, we applied a buffer of 50 m to a national map of rivers (i.e. 100 m total width), regardless of the width of the river itself. Therefore in some cases in smaller rivers this might be slightly conservative, but in other places with large rivers, this would be an underestimate of the generally agreed 20 m river buffer (DWAF 2008). Therefore, although not perfect, it gives a rough indication of potential water savings with compliance. The national map of rivers is called the ”WRIAL500” (Water Resource Inventory at a 1:500,000 scale) dataset, a publicly-available hydrological vector dataset that represents South Africa’s river networks at a medium-scale resolution (https://www.dws.gov.za/iwqs/gis_data/river/rivs500k.aspx). This dataset includes both perennial and non-perennial rivers. The river data were clipped to the extent of each of our four study catchments in ArcGIS Pro, and the buffers applied. Area of woody alien plant invasions and plantations within the buffer zones were calculated, and expressed as a percentage of the entire network of buffer zones per catchment. Based on these area values, and the relative water use of two alien classes used as plantations across all four catchments (i.e. gum and pine) compared to the wetland class, the total volumetric water impact per annum was estimated.

4. STUDY SITES

The four project study catchments span four provinces (**Figure 5**, **Table 3**) different biomes (forest, grassland, savanna), a range of different climates (bimodal to summer-rainfall), soils and socio-economic contexts/land-uses.

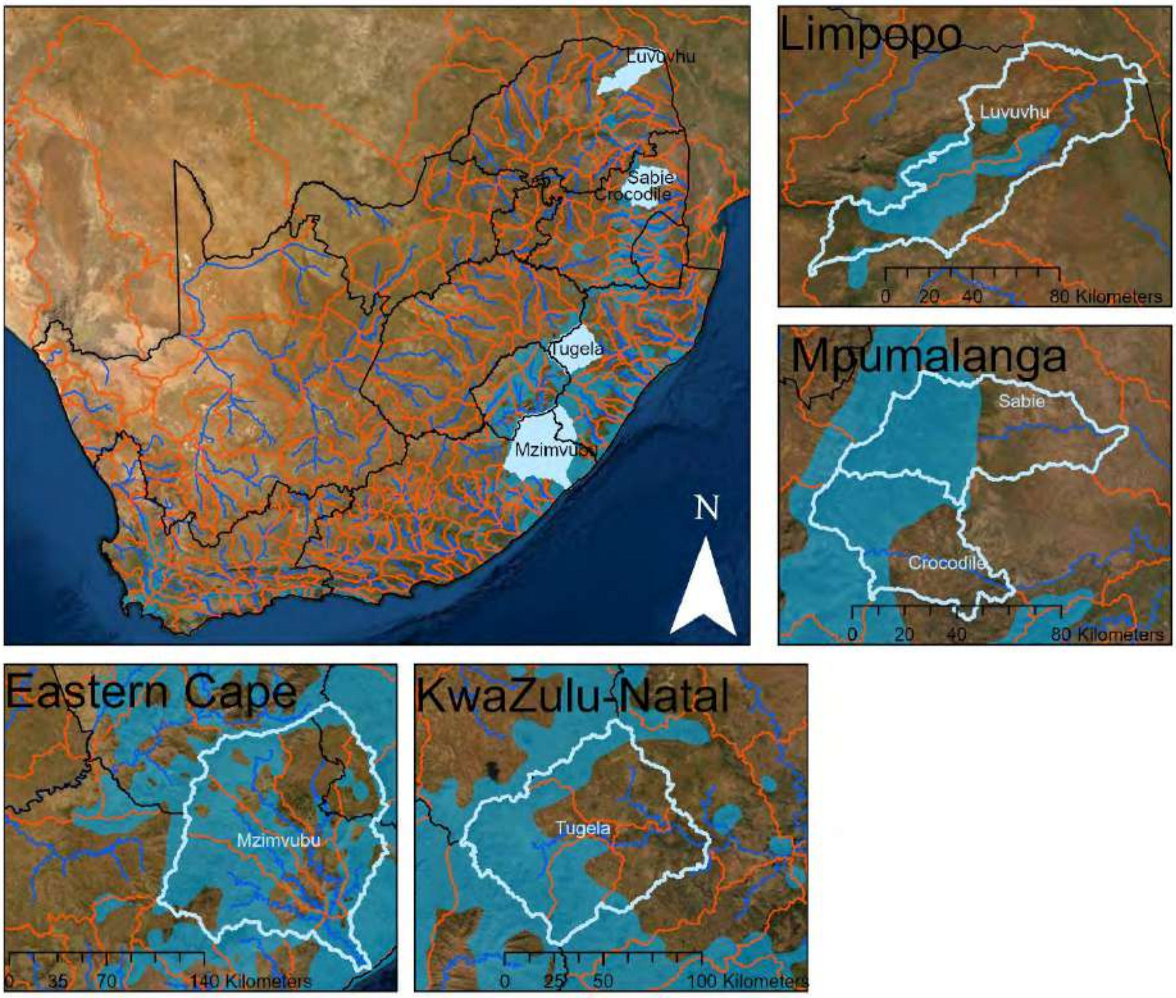


Figure 5. *The four final study site catchments within strategic water source areas in South Africa. The surface water strategic water source areas are indicated by blue polygons, tertiary catchments by orange lines, provinces in black, and the major rivers in dark blue.*

Table 3. *Details of the four study catchments, including catchment codes for reference to external databases.*

Primary Catchment	Secondary Catchment	Catchment Name	Province	Area (km^2)
A	A9	Luvuvhu	Limpopo	5693.46
X	X2	Crocodile	Mpumalanga	2368.67
X	X3	Sabie	Mpumalanga	2960.56
T	T3	uMzimvubu	Eastern Cape	19839.72
V	V1	Tugela	KwaZulu-Natal	7617.00

4.1. Luvuvhu Catchment

For the Luvuvhu Catchment we added the Soutpansberg due to stakeholders indicating the invasive alien tree problem in the mountainous region. However the results given in this report are clipped to the Luvuvhu Catchment as these are the accepted national boundaries. The fieldwork yielded a training dataset of 4870 points in 18 classes for the Luvuvhu Catchment plus the Soutpansberg (**Figure 6**). The Luvuvhu Catchment is divided into two distinctive regions in terms of bioclimate and topography: the north-east and the south/central. The north-east is more arid with less variable topography and extensive areas of bare ground and small patches of grasses. Indigenous bush consists primarily of homogenous *Colophospermum mopane* thickets, while other taxa such as *Combretum sp., Vaechellia sp., Senegalia sp., Dichrostachys cinerea*, and *Adansonia digitata*, are more sparsely distributed (**Plate 1**). The major land-use in the north-eastern regions of the catchment is dryland agriculture, and these activities are often small community or residential croplands that include subsistence beans, maize, and other leafy vegetables.

The south/central region has higher rainfall and variable topography around the Soutpansberg Mountains dominated by indigenous bush, with narrow bands of indigenous forest on the mountains. The Soutpansberg Mountains are a water tower (areas with disproportionately high runoff globally, Viviroli et al. 2011), and fall within a surface water strategic water source area (**Plate 2**). In contrast to the north-east, the indigenous bush in the wetter central and southern region of the catchment is more heterogenous and consists of different mixtures of *Dichrostahcys cinerea, Terminalia sericea, Vaechellia sp., Senegalia sp., Euphorbia sp., Aloe sp., Dovyalis sp., Agave sp.*, and *Cereus jamacaru*. However, the dominant bush taxon is *Dichrostahcys spp*., making up over half of the cover. This region has many wetlands; however these are in poor condition, largely due to overexploitation by agricultural activities as well as rural settlements built adjacent to, or within, the wetlands. In terms of land-use, these are diverse but dominant types include large-scale agricultural activities such as orchards, and gum and pine plantations.

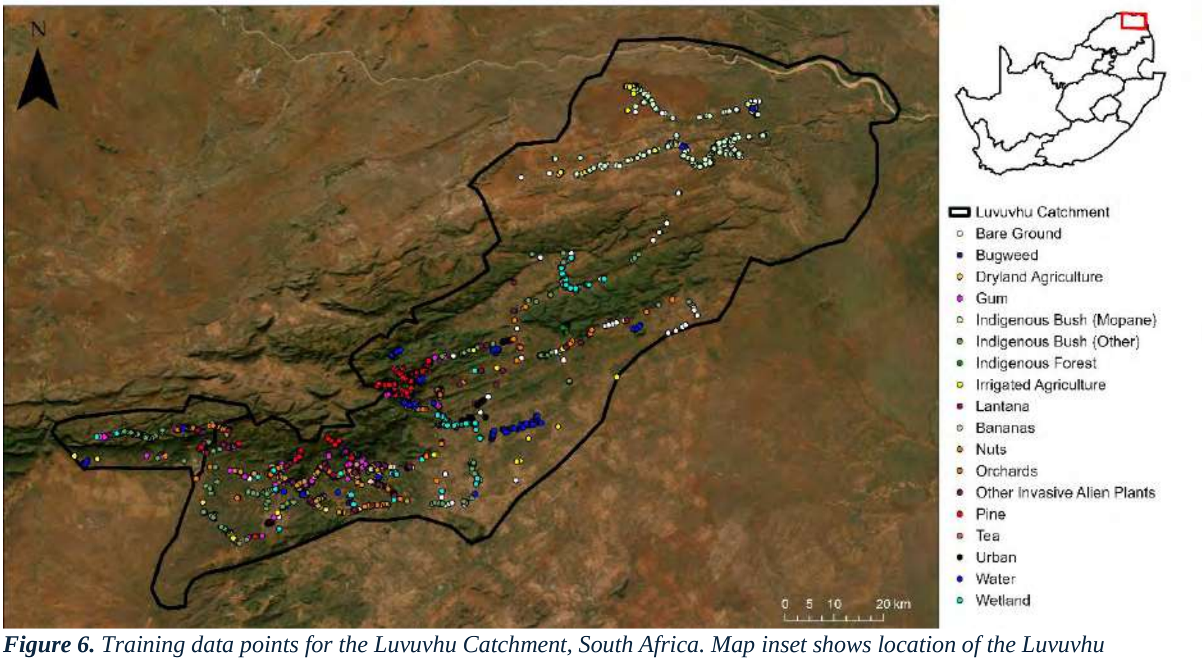


Figure 6. *Training data points for the Luvuvhu Catchment, South Africa. Map inset shows location of the Luvuvhu Catchment. The Soutpansberg has been added to the Luvuvhu Catchment on the bottom right as indicated by the extension to the catchment boundary.*

4.1.1. Stakeholder inputs

A total of 13 individuals attended the virtual Luvuvhu stakeholder workshop, representing different organisations including Endangered Wildlife Trust (EWT), the University of Venda (UNIVEN), Naledzi Environmental Consultancy, and the South African Forestry Company Limited (SAFCOL). Stakeholders listed the following woody invasive alien plant taxa as the top priorities to map: *Pinus spp*., *Eucalyptus spp.*, *Lantana camara*, *Solanum mauritianum*, *Chromolaena odorata*, and *Biancaea decapetala* (**Table 4**). Other lower priority, potentially emergent, taxa were also raised and discussed which included among others, *Acacia mearnsii*, *Psidium guajava*, *Ricinus communis*, *Senna spp.*, and *Arundo donax*. Stakeholders also raised the point that there is potentially also significant bush encroachment of indigenous species occurring in the catchment.

Table 4. *Details of the key invasive plant taxa that were listed at the Luvuvhu stakeholder workshop, including stakeholder appointed priority status, and whether the taxon is an alien or not. Colours relate to the priority status.*

Key Taxon	Latin Name	Growth	Priority	Native
Bugweed	*Solanum*	Woody shrub	1	No
Gum	*Eucalyptus spp*	Tree	1	No
Lantana	*Lantana camara*	Broadleaf	1	No
Mauritious Thorn	*Biancaea*	Climber	1	No
Pine	*Pinus spp*	Tree	1	No
Triffid Weed	*Chromolaena*	Broadleaf	1	No
Black Wattle	*Acacia mearnsii*	Tree	2	No
Castor bean	*Ricinus communis*	Shrub	3	No
Fever Tree	*Lippia javanica*	Woody	3	Yes
Flame Thorn	*Senegalia*	Tree	3	Yes
Giant Milkweeds	*Calotropis procera*	Shrub	3	No
Giant Reed	*Arundo donax*	Reed	3	No
Giant Sensitive	*Mimosa pigra*	Woody	3	No
Guava	*Psidium guajava*	Tree	3	No
Jacaranda	*Jacaranda*	Tree	3	No
Mexican	*Tithonia spp*	Herbaceous	3	No
Muhua	*Vangueria infausta*	Woody	3	Yes
Senna	*Senna spp*	Shrub	3	Mixed
Sickle Bush	*Dichrostachys*	Tree	3	Yes
Silky Oak	*Grevillea robusta*	Tree	3	No
Silver cluster leaf	*Terminalia sericea*	Tree	3	Yes
Yellow Bells	*Tecoma stans*	Shrub	3	No

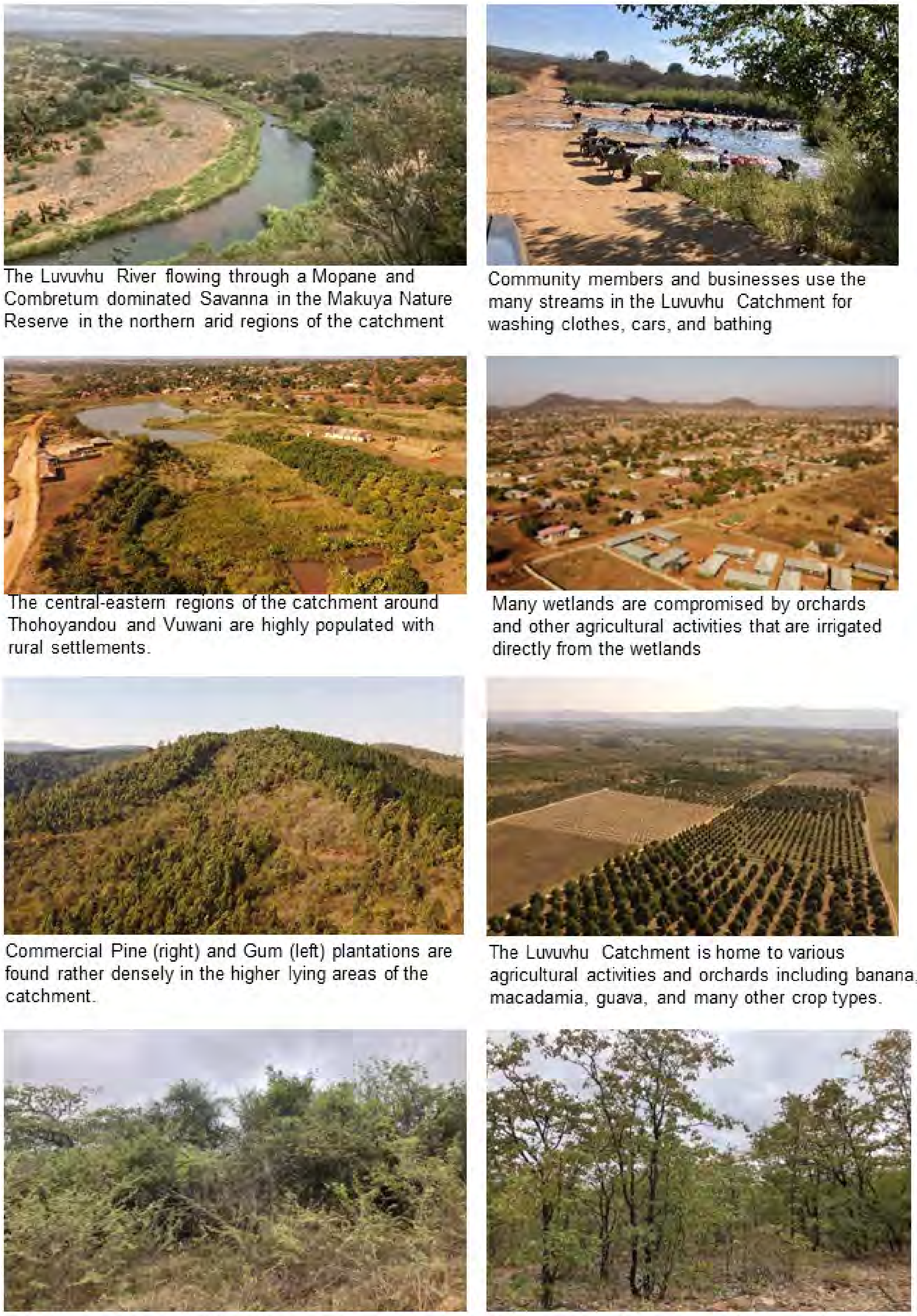
Based on stakeholder inputs, 20 classes were selected for the Luvuvhu Catchment to maximise woody invasive alien plant mapping accuracy (**Table 5**). This included seven woody invasive alien plant classes, specifically: gum (*Eucalyptus spp*), pine (*Pinus spp*), Lantana (*Lantana camara*), Triffid Weed (*Chromolaena odorata*), Bugweed (*Solanum mauritianum*), and Mauritius Thorn (*Biancaea decapetala*), and an additional "bin" class for all 'Other Invasive Alien Plants'. Due to the high number of easily distinguishable agricultural types in the Luvuvhu Catchment, as well as the fact that training data were easily collectable, we decided to separate these into distinct classes. However, distinguishing agricultural classes was not the main aim of this work. Agricultural classes included: tea, dryland agriculture (mostly comprised of pastureland), irrigated agriculture (mostly comprised of maize, beans, and other leafy vegetables), and different orchards including banana and nut trees (macadamia and pecan). Due to differences in bush characteristics in the two different regions, we created two separate indigenous bush classes, namely, 'Indigenous Bush (Mopane)', to represent indigenous bush in the north-east regions; and 'Indigenous Bush (Other)', to represent indigenous bush in the south/central regions.

Table 5. *The final land-use/land-cover key for the fieldwork in the Luvuvhu Catchment, with a total of 4870 points for the 18 classes.*

Hex Code	#	Class	Points	Description
#FEE238	1	Dryland Agriculture	300	Rangelands and open grasslands
#ffff00	2	Irrigated Agriculture	300	Irrigated maize, beans, and other leafy crops
#ffcc99	3	Bananas	300	Banana orchards
#DB992D	4	Nuts	300	Macadamia and pecan orchards
#ff7f00	5	Orchards	300	Various orchards including guava, mango, avocado, and citrus crops
#D16E37	6	Tea	300	Tea estates
#ccffb3	7	Indigenous Bush (Mopane)	300	*Colophospermum mopane* dominated bushveld with lower densities of *Combretum spp*, *Vachellia, Dichrostachys, Aloe*, and *Adansonia spp*
#6aa84f	8	Indigenous Bush (Other)	300	Heterogenous bushveld made up of *Dichrostachys, Vachellia, Terminalia, Dovyalis, Cereus, Aloe*, and other genera
#14870e	9	Indigenous Forest	300	*Neocussonia spp, Combretum spp*, and other indigenous forest genera
#0a14f9	10	Water	300	Waterbodies
#08f3e4	11	Wetland	300	Natural wetlands
#FFFFFF	12	Bare Ground	300	Quarries, excavated areas, gravel roads, gullies
#000000	13	Urban	300	Built-up areas, infrastructure, roads
#fd0618	14	Pine	300	Pinus spp including *P. patula*
#980A7D	15	Lantana	120	*Lantana camara*
#351C75	16	Bugweed	80	*Solanum mauritianum*
#F91DF9	17	Gum	300	*Eucalyptus. grandis, E. camaldulensis* and other *Eucalyptus spp*
#741b47	18	Other Invasive Alien Plants	170	*Chromolaena odorata, Senna didymobotrya, Biancaea decapetala*, and *Ricinus communis*

4.1.2. In-field invasive alien plant observations

In the north-east region there were relatively few woody invasive alien plants. Where there are invasions in this region, they are cleared with support from conservation initiatives including teams from Kruger National Park. However, in the south/central region the alien plant invasions are diverse and extensive. The dominant species are escapees from forestry plantations (e.g. pine and gum), however other taxa include *Lantana camara* and *Biancaea decapetala*, mainly along disturbed road verges and the edges of orchards, fence lines, and urban areas and can at many times be found mixed with *Solanum mauritianum, Senna didymobotrya*, and *Ricinus communis*. Besides growing in dense, monospecific stands under pine and gum plantations, *L. camara* also occurs in on fallow land and in firebreaks and *B. decapetala* in ravines and among indigenous forest, orchards and plantations. This made it challenging to obtain pure pixel training data of both species. *Solanum mauritianum* is found in plantations under the canopy but can also form dense infestations in disturbed plantation areas such as where harvesting takes place. *Chromolaena odorata* was found to be at the highest density in the central regions of the catchment around Thohoyandou, also tending to invade disturbed road verges. Many other invasive alien plant species were observed, but less frequently and in less extensive stands. These species included *Acacia elata, Populus canescens*, and *Bambusa spp*.



The Luvuvhu River flowing through a Mopane and Combretum dominated Savanna in the Makuya Nature Reserve in the northern arid regions of the catchment

Community members and businesses use the many streams in the Luvuvhu Catchment for washing clothes, cars, and bathing

The central-eastern regions of the catchment around Thohoyandou and Vuwani are highly populated with rural settlements.

Many wetlands are compromised by orchards and other agricultural activities that are irrigated directly from the wetlands

Commercial Pine (right) and Gum (left) plantations are found rather densely in the higher lying areas of the catchment.

The Luvuvhu Catchment is home to various agricultural activities and orchards including banana, macadamia, guava, and many other crop types.

Indigenous bushveld in the central and southern regions of the catchment are rather heterogenous comprised of *Vaechellia, Senegalia, Dichrostachys cinerea, Terminalia sericea, Dovyalis, Euphorbia*, and many others.

The northern arid regions of the catchment are primarily comprised of *Colophospermum mopane* and *Combretum* species..

Plate 1. *Photos of landscape and socio-ecological observations in the Luvuvhu Catchment, South Africa.*

Large *Eucalyptus camaldulensis* trees invading a steep rock face in the Happy Rest Nature Reserve in the Soutpansberg

Extensive *Pinus patula* plantation with two large, isolated bamboo stands (featured on the right)

A dense mixture of *Lantana camara* and *Solanum mauritianum* growing under the canopy of a young *Pinus patula* plantation

Dense *Solanum mauritianum* growing under the canopy of *Pinus patula*

Solanum mauritianum growing along the slopes of a previously timber harvested compartment in a *Eucalyptus* plantation

Lantana camara infestation forming a dense blanket under the canopy of thorny *Vachellia* Savanna trees. No grasses or other indigenous plants can be seen in the area.

Biancaea decapetala growing over orchard trees

Dense *Chromolaena odorata* stand growing on the road verges.

Plate 2. *Photos showing characteristic alien plant invasions in the Luvuvhu Catchment, South Africa.*

4.2. Sabie-Crocodile Catchment

The Sabie and Crocodile catchments were amalgamated into one study site for this project and is hereafter referred to as the Sabie-Crocodile Catchment. The fieldwork yielded a training dataset of 4467 points in 17 classes (**Figure 7**). The eastern part of the study catchment (Kruger National Park, Bushbuckridge Ridge Nature Reserve and Sabi Sand Nature Reserve) is dominated by indigenous bush, with dense indigenous forest on the steep slopes just below the escarpment near Sabie and Graskop. Indigenous bush in the catchment is comprised of *Vachellia spp., Dichrostachys cinerea* (Sickle Bush), *Diospyros mesilformis* (Jackel Berry), *Combretum hereroense* (Russet Bushwillow), *Euclea divinorum* (Magic Guarri), *Acacia sieberiana* (Paperbark acacia) and *Senegalia ataxacantha* (Flame Thorn Tree). Winter burns are common in the catchment in winter, which is the dry season. The main land-use in the Sabie-Crocodile Catchment is commercial forestry plantations, specifically pine and gum, and most of these are located in the west of the study catchment, just below the escarpment in the lowveld. Orchards are also common, including macadamias which were widespread, bananas (located more in the central parts of the catchment), as well as mangoes, avocados and litchis. In general, it is a densely populated region, with many towns and a large tourism industry.

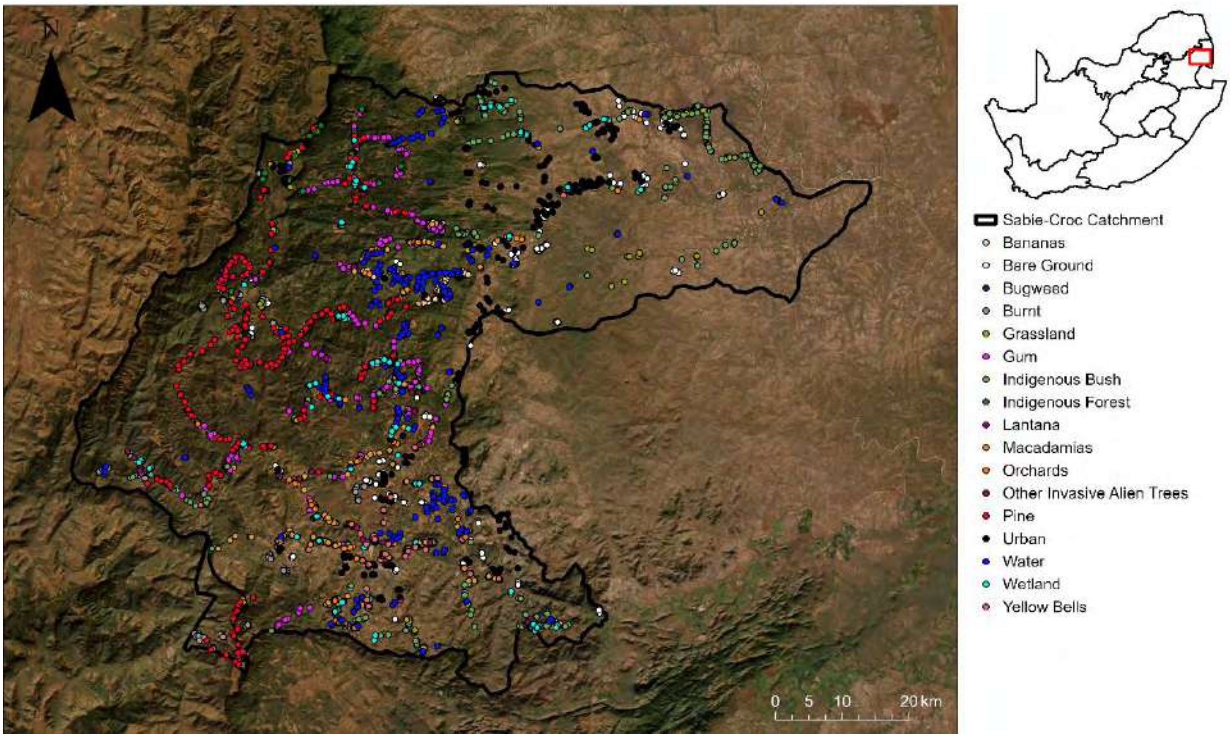


Figure 7. *Training data points for the Sabie-Crocodile Catchments, South Africa. Map inset shows location of the Sabie-Crocodile Catchments.*

4.2.1. Stakeholder inputs

A virtual stakeholder workshop was attended by over 20 participants from various organizations such as Kruger2Canyons, the Department of Forestry, Fisheries and the Environment, BirdLife and the South African Forestry Company Limited (SAFCOL). Stakeholders identified key invasive alien plants as *Pinus* spp. (pines). *Eucalyptus* spp. (gums), *Acacias* (wattles), *Solanum mauritianum* (Bugweed) and *Lantana camara* (**Table 6**). Stakeholders advised that pines are generally found on the escarpment near commercial forestry plantations. Gums were said to be located more generally on the foothills, at lower altitudes compared to pines. Bugweed was said to be in plantations (under the canopy), and in drainage areas where brush clearing has occurred. Lantana is widespread throughout the catchment according to stakeholders.

Table 6. *Details of the key invasive plant taxa that were listed at the Sabie-Crocodile stakeholder workshop, including stakeholder appointed priority status, and whether the taxon is an alien or not. Colours relate to the priority status.*

Key Taxon	Latin Name	Growth	Priority	Native
Bugweed	*Solanum mauritianum*	Tree	1	N
Gums	*Eucalyptus saligna, + other spp mixtures*	Tree	1	N
Lantana	*Lantana camara*	Herb	1	N
Pine	*P. patula, P. eliotii (not spreading so*	Tree	1	N
Seringa	*Melia zadorac*	Tree	1	N
Wattle	*A. mearnsii, A. melanoxylon*	Tree	1	N
Blackwood	*Acacia melanoxylon*	Tree	2	N
Mexican Poppy	*Tethania mexicana; T diversifolia*	Herb	2	N
Poplar	*P canescens hybrid, and a few others*	Tree	2	N
Triffid weed	*Plant*	Herb	2	N
African Flame	*Spathodea campanula*	Tree	3	N
Bramble	*Rubus niveus*	Herb	3	N
Famine weed	*Parthenium hysterophorus*	Herb	3	N
Guava	*Psidium guajava*	Tree	3	N
Ironwood	*Casurina*	Tree	3	N
Jacaranda	*Jacaranda mimisofolia*	Tree	3	N
Mauritius Thorn	*Biancaea decapetala*	Tree	3	N
Mulberry	*Morus nigra*	Tree	3	N
Pompom Weed	*Campuloclinium macrocephalum*	Herb	3	N
Prickly Pear	*Opuntia*	Succulent	3	N
St. Joseph's Lily	*Lilium formosanum*	Herb	3	N
Yellow Bells	*Tecoma stans*	Shrub	3	N

Selected classes included pines, gums, wattle, Bugweed and Lantana (as the key invasive alien taxa of concern), as well as an “Other Invasive Alien Tree” bin class for other aliens which are problematic but do not appear in such dense stands (such as Trifid Weed and Mexican Poppy) (**Table 7**). During the fieldwork campaign, an extensive infestation of Yellow Bell (*Tecoma stans*) was observed in Mbombela, and consequently it was added as a class. Due to large numbers of both Macadamia and Banana orchards in the catchments, these classes were separated. The “Orchards” class is comprised of other orchards in the catchment that were not dominant, including: avocados, mangoes, and litchi. Given that the upper part of the catchment was extensively burnt during the field work period (winter burns), a “burnt” class was added to account for this.

Table 7*. The final land-use/land-cover key for the fieldwork in the Sabie-Crocodile Catchment, with a total of 4467 points for the 17 classes.*

Hex Code	#	Class	Points	Description
#ffcc99	1	Bananas	300	Banana orchards
#DB992D	2	Macadamias	300	Macadamia orchards
#ff7f00	3	Orchards	300	Mix of mangoes, avocados and litchi orchards
#a8a800	4	Grassland	300	Natural grassland and grazing land
#6aa84f	5	Indigenous Bush	300	*Vachellia spp., Dichristachys cinerea, Diospyros mesilformis, Combretum hereroense, Euclea divinorum, Acacia sieberiana,* and *Senegalia ataxacantha*
#14870e	6	Indigenous Forest	300	Mix of *Nuxia* spp, *Brachylaena transvaalensis, Rawsonia* spp and other indigenous forest species
#0a14f9	7	Water	300	Waterbodies
#08f3e4	8	Wetland	300	Natural wetlands
#ffffff	9	Bare Ground	300	Mines, quarries, rock, gravel roads, gullies
#000000	10	Urban	300	Built-up areas, infrastructure, roads
#99999	11	Burnt	300	Burnt areas
#fd0618	12	Pine	300	*Pinus* spp.
#F91DF9	13	Gum	300	*Eucalyptus* spp.
#351C75	14	Bugweed	132	*Solanum mauritianum*
#980A7D	15	Lantana	102	*Lantana camara*
#E06666	16	Yellow Bells	271	*Tecoma Stans*
#741b47	17	Other Invasive Alien Plants	62	Mix *of Rubus spp., Chromolaena ordata, Acacia spp., Populus spp., Senna didymobotrya*

4.2.2. In-field invasive alien plant observations

Similarly to the Luvuvhu Catchment, the eastern part of the catchment was observed to lack large stands of woody invasive alien plants. Plantations of *Eucalyptus* spp. and *Pinus* spp. are common in the upper part of the catchment (in the west) (**Plate 3**). A few isolated *Eucalyptus* spp infestations were observed, invading farms or along roadsides. *Acacias* did not appear to form dense stands in this region (unlike in KwaZulu-Natal and the Eastern Cape), they were mostly found as single trees or a small stand of trees within pine and gum plantations. Wattle seedlings were also observed to be emerging in a burnt patch within a pine plantation. *Solanum mauritianum* (Bugweed) invasions were mainly associated with plantations (**Plate 4**). They occur as understory invaders and proliferate in areas where timber has been harvested, using these locations and short timeframes to recruit between rotations. Bugweed was also sighted invading orchards, but relatively sparsely. *Lantana camara* was common, prevalent along roads and fence lines and within plantations. In some instances, Lantana and Bugweed were found to coexist relatively well and mixed stands were observed. On the R40 to Bushbuckridge, Lantana was also observed to be co-existing with Triffid Weed (*Chromolaena odorata*). Lantana was also found to be mixing with indigenous bush. *Tecoma stans* (Yellow Bells) were quite common in the catchment, especially in Mbombela, particularly along disturbed road edges and in orchards. Other invasive alien plants found in the catchments included Bramble in plantations, Trifid Weed and Peanut Butter Cassias (*Senna didymobotrya).*

Plate 3. *Photos of landscape and socio-ecological observations in the Sabie-Crocodile Catchments, South Africa. Clockwise from left to right: plantations with some clear-felled sites in the foreground, orchards, indigenous bush, indigenous forest, indigenous forest in valleys between plantations, and a populated township near Hazyview, South Africa.*

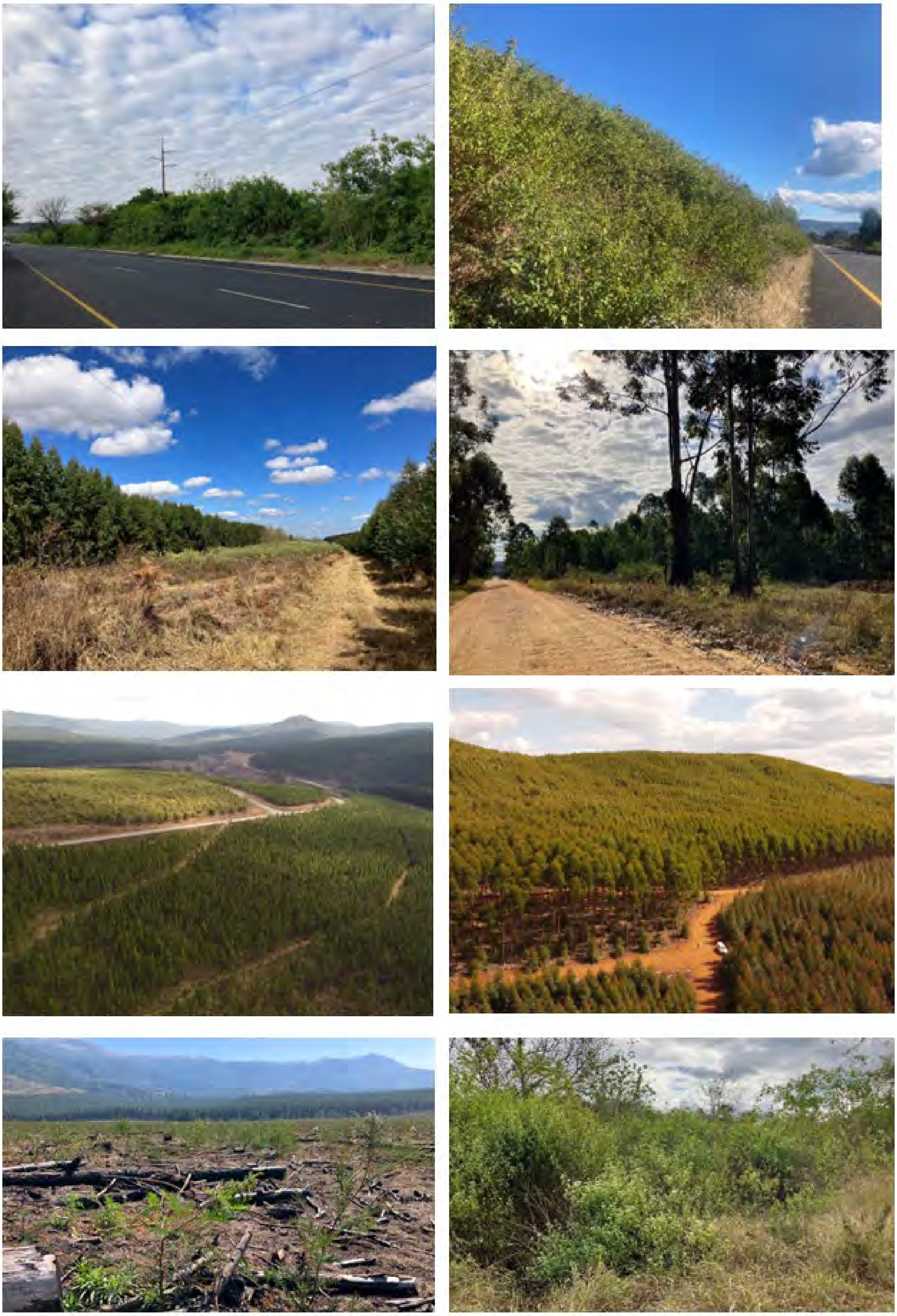


Plate 4. *Photos showing characteristic alien plant invasions in the Sabie-Crocodile Catchments, South Africa. Clockwise from top to bottom: Yellow Bells along the road,* Lantana camara *on a road verge, Bugweed infestation in a plantation, gum infestation along the road, pine plantation, gum plantation, wattle seedlings growing after fire, and a Trifid Weed infestation mixed in with indigenous bush.*

4.3. Tugela Catchment

The fieldwork yielded a training dataset of 4967 points and 17 classes (**Figure 8**). Grasslands are extensive in the Drakensberg Mountains and the lowlands. Many of these grasslands are used as rangelands. Gully erosion is a common sight in the catchment. Indigenous forest occurs within fire-protected ravines in the Drakensberg mountains. Indigenous bush is another common vegetation type in the catchment. Two broad groups emerged, bush dominated by *Vachellia spp*. and that dominated by *Leucosidea spp.* (**Plate 5**). *Vachellia spp.* tends to grow densely in the more arid regions of the catchment such as the northeast and central regions around Ladysmith-Colenso, and Spionkop respectively. *Leucosidea spp.* occurs in patchy and mixed thickets with other indigenous bush species such as Sagewood, and False Assegai. *Pteridium aquilinum* occurs in the more mountainous regions of the catchment and was observed to be associated with recently burnt areas as well as drainage lines and some wetlands.

The major land-use types in the Tugela Catchment consist of irrigated agriculture, such as maize, wheat, rye, soya, potatoes, and pasture/cover crops for livestock feeding. These agricultural industries are highly dependent on fresh water sources. Dryland (i.e. rainfed) agriculture mainly consists of non-irrigated grasslands for grazing, but this is dependent on rainfall to successfully support livestock or game. Wattle stands, particularly *Acacia mearnsii*, are grown within or next to communities in woodlots for firewood (**Plate 6**). Additionally, stakeholders shared that poles are of ceremonial importance, as they are used in burial ceremonies where the wood is placed between a coffin and the earth to act as a buffer. Poplar trees are also favoured by communities to an extent, and are grown as a source of timber for building houses or furniture, as well as for poles.

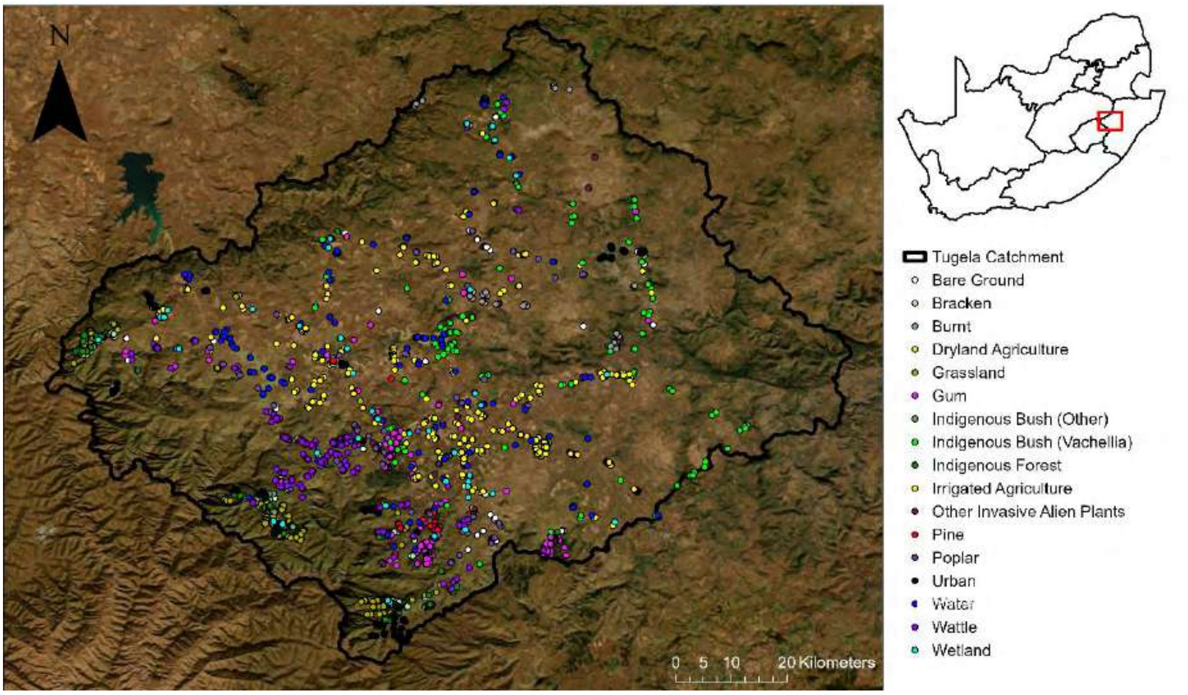


Figure 8. *Training data points for the Tugela Catchment, South Africa. Map inset shows location of the Tugela Catchment.*

4.3.1. Stakeholder inputs

The virtual Tugela stakeholder workshop was attended by eight individuals from different organisations, representing: the Institute for Natural Resources (INR), Wildtrust, South African Environmental Observation Network (SAEON), and Ezemvelo KwaZulu-Natal Wildlife (EKZNW). The invasive alien plant taxa of greatest concern to the stakeholders seemed to be primarily woody taxa, mainly due to increasing fuel load and thereby fire risk, as well as related water impacts. The woody invasive alien plant taxa such as wattles and poplars for example, grow extensively along rivers and streams and within wetlands, where they consume significant quantities of water that the communities and farmers are dependent on for survival. It was therefore concluded that the most concerning invasive alien plant taxa were: wattles, pines, gums, bramble, and Lantana (**Table 8**, **Table 9**). The taxa of lesser concern included, but were not limited to: poplar, willow, Syringa, and Bugweed.

Table 8. *Details of the key invasive plant taxa that were listed at the Tugela stakeholder workshop, including stakeholder appointed priority status, and whether the taxon is an alien or not. Colours relate to the priority status.*

Key Taxon	Latin Name	Growth	Priority	Native
Black Wattle	*Acacia mearnsii*	Tree	1	No
Bracken Fern	*Pteridium aquilinum*	Broadleaf	1	Yes
Bramble	*Rubus spp*	Broadleaf	1	No
Gums	*Eucalyptus spp*	Tree	1	No
Lantana	*Lantana camara*	Broadleaf	1	No
Pine	*Pinus spp*	Tree	1	No
Silver Wattle	*A. dealbata*	Tree	1	No
Poplar	*Populus spp*	Tree	2	No
Sweet thorn	*Vachellia karroo, V. sieberiana*	Tree	2	Yes
Willow	*Salix spp*	Tree	2	*
Agave	*Agave spp*	Succulent	3	No
Bahia Grass	*Paspalum notatum*	Grass	3	No
Bugweed	*Solanum mauritianum*	Tree	3	No
Calpurnia	*Calpurnia aurea & Calpurnia*	Broadleaf	3	Yes
Cotoneaster	*Cotoneaster*	Herb	3	No
European	*Ulex europaeus*	Shrub	3	No
False Assegai	*Maesa lanceolata*	Broadleaf	3	Yes
Ginger species	*Zingiber spp*	Herb	3	Yes
Hypericum	*Hypericum pseudohenryi, H. patulatum and one other*	Herb	3	No
Ouhoudt	*Leucosidea sericea*	Shrub/Tree	3	Yes
Pompom Weed	*Campuloclinium macrocephalum*	Herb	3	No
Poormans	*Lespedeza cuneata*	Forb/legume	3	No
Protea	*Protea cafra*	Shrub/tree	3	Yes
Sagewood	*Buddleja salviifolia*	Broadleaf	3	Yes
Scotch Broom	*Cytisus scorapius*	Shrub	3	No
Syringa	*Melia azederach*	Tree	3	No
Triffid Weed	*Chromolaena odorata*	Shrub	3	No

The concern around potential bush encroachment was also raised, where certain stakeholders have observed that indigenous bush taxa such as *Vachellia* species and *Pteridium aquilinum* had been densifying across the catchment. Other indigenous bush taxa include various *Aloe spp, Protea* woodland spp, *Agave spp, Leucosidea sericea, Culpurnea*, and *Buddelja* (**Plate 5**). We separated indigenous bush into two different subclasses: ‘Indigenous Bush (Vachellia)’ (for areas where Thorny Acacias were dominant), and ‘Indigenous Bush (Other)’ for areas where Ouhoudt, or Protea woodland was dominant. Stakeholders also mentioned extensive erosion gullies (locally “dongas”) in the catchment which are believed to be a result of overgrazing and other stresses such as fires and floods, and that this could cause large areas of ‘bare ground’, which we therefore included as a class.

The top priority invasive alien plant taxa chosen for mapping included gums (*Eucalyptus spp*), pines (*Pinus spp*), wattles (including *Acacia mearnsii, A. decurrens*, and *A. dealbata*), Bramble (*Rubus spp*), and Lantana (*Lantana camara*) (**Table 8**, **Plate 6**). Lower priority taxa such as poplar (including *Populus canescens*, *P. nigra*, and *P. alba*), Syringa (*Melia azedarach*), Triffid Weed (*Chromolaena odorata*), Bugweed (*Solanum mauritianum*), and any other invasive alien plant taxa were included collectively in a bin class namely, ‘Other Invasive Alien Plants’.

Table 9. *The final land-use/land-cover key for the fieldwork in the Tugela Catchment, with a total of 4967 points for the 17 classes.*

Hex Code	#	Class	Points	Description
#FEE238	1	Dryland Agriculture	300	Rangelands
#ffff00	2	Irrigated Agriculture	370	Potatoes, Rye, Wheat, Soya
#a8a800	3	Grassland	300	Natural grasslands
#6aa84f	4	Indigenous Bush (Other)	300	Mix of *Leucosidea spp, Maesa lanceolata, Buddleja spp* and other genera
#00FF00	5	Indigenous Bush (Vachellia)	300	*Vachellia* (*V. karoo, V. sieberiana, V. nilotica*) dominated bushveld
#A8EFA6	6	Bracken	300	*Pteridium aquilinum*
#14870e	7	Indigenous Forest	300	Mix of *Podocarpus spp, Afrocarpus spp, Cyathea spp*, andother indigenous forest spp.
#0a14f9	8	Water	300	Waterbodies
#08f3e4	9	Wetland	300	Natural wetlands
#FFFFFF	10	Bare Ground	300	Mines, quarries, rock, gravel roads, gullies
#000000	11	Urban	300	Built-up areas, infrastructure, roads
#fd0618	12	Pine	300	Pines including *P. patula* and *P. roxburghii*
#674EA7	13	Poplar	300	Poplar including *P. nigra,* P. *canescens,* and *P. alba*
#9900FF	14	Wattle	300	*Acacia mearnsii, A. dealbata,* and *A. decurrens*
#F91DF9	15	Gum	300	*Eucalyptus. grandis, E. camaldulensis, E. dunnii,* and *E. macarthurii*
#741b47	16	Other Invasive Alien Plants	97	*Lantana camara, Melia azedarach* and *Robinia pseudoacacia*
#99999	17	Burnt	300	Burned areas

4.3.2. In-field invasive alien plant observations

Woody invasive alien plant species in the Tugela Catchment are diverse and found frequently across the landscape, especially in previously disturbed environments. The most widespread taxa are various wattle species, such as: *Acacia mearnsii, A. dealbata*, and *A. decurrens*. The most dominant of these appears to be *A. mearnsii*, although in many cases mixed stands are present, with *A. dealbata* and *A. decurrens*. This means that often it was a challenge to collect data from pure *A. mearnsii* stands. The *A. dealbata* also seems to be rather dominant and accounts for many of the stands in the catchment, whilst *A. decurrens* occurs less frequently and in much more isolated infestations particularly in the Royal Natal and Injisuthi regions of the catchment. Besides wattle, gums are found rather frequently across the catchment and is perhaps the most common and evenly distributed woody invasive. Large gum plantations can be found in the southwest regions of the catchment, but several isolated private gum plantations occur throughout the catchment as well. After gum and wattle, poplar trees are also widespread in the catchment, occurring mostly in wetlands, drainage lines and along streams and rivers. This genus was first thought to be relatively unimportant, but fieldwork observations revealed that it is was very extensive and dense.

Similarly, Black Locust (*Robinia pseudoacacia*) and Syringa (*Melia azedarach*) seem to thrive in water courses and can form particularly dense thickets along river crossings and road verges that are in the vicinity of wetlands and riparian zones. Alien bramble occurred in hotspots in the Injusthi, Cathedral Peak, and Royal Natal areas mostly, but was often found in areas that were recently burnt or growing in mixed stands with the fern *Pteridium aquilinum*. This made it difficult to obtain many pure pixels of bramble in the catchment. *Lantana camara* was similarly difficult to find in dense infestations. Lantana formed isolated patches of about 2-3 m in diameter and 1.5 m in height. The most prevalent and dense Lantana infestations were northeast of Injisuthi and on the higher slopes of the Khwela and Emmaus community areas. Pine trees were mostly found in forestry plantation blocks. There were no dense infestations outside of the forestry plantations, but many isolated trees were found throughout the eastern, central, and western regions of the catchment, particularly in the mountain reserves.

A view of Cathedral Peak with strips of indigenous forest (darker green patches along the slopes) and patches of Protea woodland (lighter sparse patches along the slopes).

Dense stands of *Vachellia karoo, V. siberiana*, and *V. nilotica* on a farm in the Winterton area.

Extensive indigenous Protea woodland growing along the slopes of the Northern Drakensberg

Pteridium aquilinum distinct from woody indigenous bush taxa such as *Vachellia* and *Protea spp*

Bulk machinery harvesting rye. The agriculture industry in the Tugela catchment is extensive and diverse.

Irrigated agriculture is fed by the multitude of streams, dams, and wetlands in the Tugela catchment.

Overgrazing can result in extensive erosion. Besides pressures from grazing along wetlands and riparian areas, invasive alien plants form dense thickets along stream banks and consume vast amounts of water.

Dongas are a fairly common site in the Tugela, where the strain from fire, overgrazing, and flooding in the area can result in significant erosion and donga formation.

Plate 5. *Photos of landscape and socio-ecological observations in the Tugela Catchment, South Africa.*

Rubus spp commonly co-occur with *Pteridium aquilinum*, especially in the Injisuthi area which is in the southwestern regions of the Tugela catchment.

A mixture of wattle including *A. mearnsii, A. dealbata*, and *A. decurrens* are found in many instances growing along the banks of rivers and streams of the central to western regions of the catchment.

Dense *Eucalyptus* plantations can be found spread throughout the Tugela catchment.

A mixture of *Populus spp* and *Melia azederach* invading drainage lines, wetlands, and streams in between farmland

Commercial *Pinus* forestry plantations can be found in infrequent compartments in the Tugela Catchment, particularly in the Cathkin Park area and is not as readily available as *Eucalyptus* plantations.

Populus and *Robinia pseudoacacia* populations infesting vast stretches of rivers.

Although, not the most dominant woody invasive alien plant in the catchment, *Robinia pseudoacacia* occurs rather densely in the central regions of the catchment where agricultural disturbance is prominent.

Lantana camara is found in isolated patches along gentle slopes that have been disturbed throughout the catchment, occurring mostly in the drier hilly areas of Khwela, Emmaus, and Winterton.

Plate 6. *Photos showing characteristic alien plant invasions in the Tugela Catchment, South Africa*

4.4. uMzimvubu Catchment

The fieldwork yielded a training dataset of 4811 points and 15 classes (**Figure 9**). In terms of vegetation, grasslands were dominant in the catchment, however they appeared highly degraded, with many erosion gullies (**Plate 7**). The northern part of the catchment had large stands of indigenous bush, specifically Ouhoudt (*Leucosidea sericea*), in some cases co-occurring with wattle, while the central part of the catchment was dominated by *Vachellia sieberiana* (Paperbark Thorn), with other common indigenous plants such as aloes and *Dovyalis spp*. The catchment is rural, with few towns. One of the most commonly observed land-use classes was subsistence, rainfed maize, which is why this was allocated its own class. Dryland agriculture, e.g. rainfed grazing for cattle, was also common. Irrigated agriculture was more common in the north-eastern part of the catchment where most of the commercial farmers are located. Irrigated agriculture types include irrigated pasture, and other leafy green vegetables.

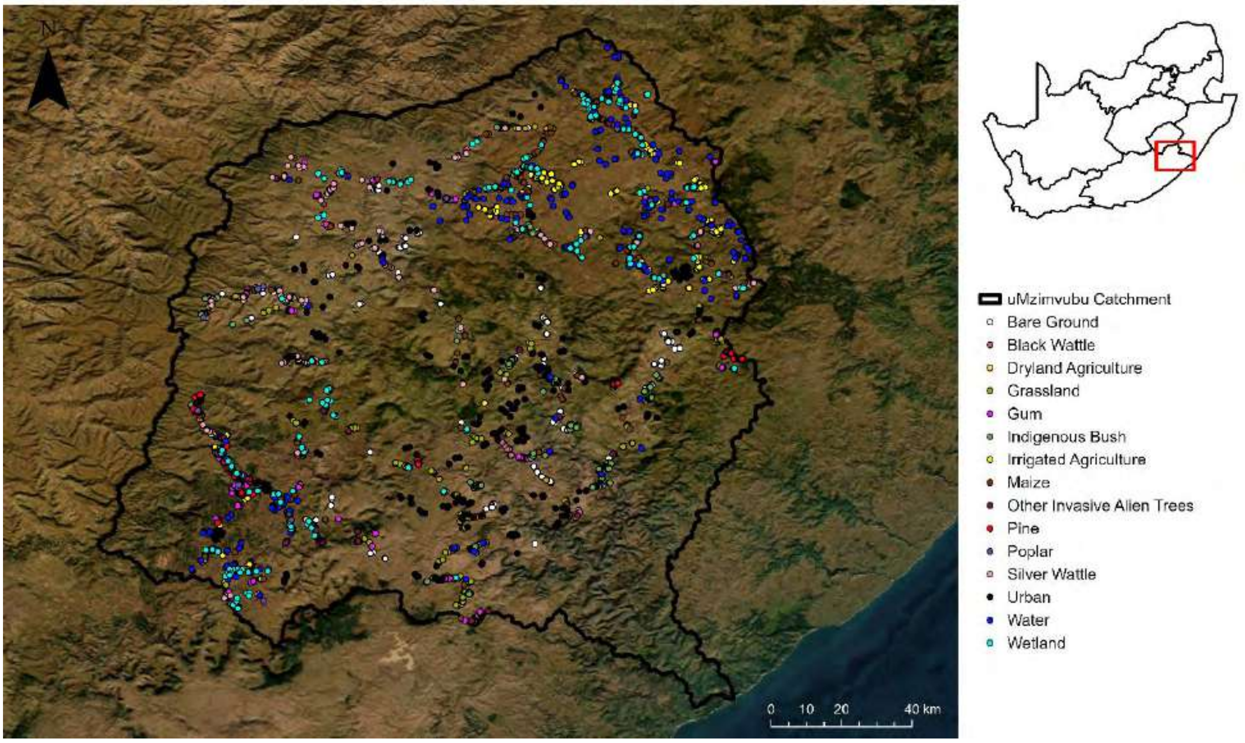


Figure 9. *Training data points for the uMzimvubu Catchment, South Africa. Map inset shows location of the uMzimvubu Catchment.*

4.4.1. Stakeholder inputs

The uMzimvubu stakeholder workshop was held in-person and formed part of the 38th uMzimvubu Catchment Partnership (UCP) meeting. The UCP program is a collaboration between 34 organizations including government, non-profit organisations, companies, rural communities and tribal authorities, and their aim is to improve land management practices and clearing of invasive alien plants in the catchments. There were over 20 stakeholders present, representing national government (e.g. Department of Forestry, Fisheries and the Environment, DFFE), non-profits like: Environmental and Rural Solutions (ERS), the World Wide Fund for Nature, Conservation South Africa, park authorities (e.g. SANParks), research organizations (e.g. the South African National Biodiversity Institute, SANBI) and academia (e.g. Rhodes University, University of KwaZulu-Natal).

Stakeholders listed the following invasive alien taxa as top priory in the catchment: *Acacia mearnsii* (Black Wattle), *Acacia dealbata* (Silver Wattle), *Pinus* spp. (pines), *Eucalyptus* spp. (gums) and *Populus* spp. (poplar) (**Table 10**, **Table 11**, **Plate 8**). Other invasive alien plant species that were an issue, but lower priority according to stakeholders were *Salix* spp. (willows), *Robinia pseudoacacia* (Black Locust), and *Lantana camara*. Black Wattle is the preferred wood for firewood, compared to Silver Wattle, for the rural communities in uMzimvubu due to the higher wood density. Therefore, stakeholders highlighted the importance and value addition to be able to distinguish Black from Silver Wattle. To date, this alien tree mapping approach has not been used to distinguish vegetation at the species level, so this was a new challenge. It was also noted by stakeholders that bush encroachment by *Leucosidea sericea* (Ouhoudt) may be occurring on some hillslopes.

Table 10. *Details of the key invasive plant taxa that were listed at the uMzimvubu stakeholder workshop, including stakeholder appointed priority status, and whether the taxon is an alien or not. Colours relate to the priority status.*

Key Taxon	**Latin Name**	**Growth Form**	**Priority**	**Native**
Black/Green Wattle	*Acacia mearnsii*	Tree	1	N
Gums	*Eucalyptus*	Tree	1	N
Silver Wattle	*Acacia dealbata*	Tree	1	N
Poplar	*Populus deltoides, canescens*	Tree	2	N
Willows	*Salix*	Tree	2	N
Black Locust	*Robinia pseudoacacia*	Tree	3	N
Bugweed	*Solanum mauritianum*	Shrub/Tree	3	N
Gifapple	*Solanum aculeastrum*	Shrub/Tree	3	Y
Hakea	*Hakea sericea*	Tree	3	N
Honey Locust	*Gleditsia triacanthos*	Tree	3	N
Lantana	*Lantana camara*	Shrub	3	N
Mauritius thorn	*Caesalpinia decapetala*	Shrub	3	N
Ouhoudt	*Leucosidea sericea*	Shrub/tree	3	Y
Pines	*Pinus*	Tree	3	N
Port Jackson	*Acacia saligna*	Tree	3	N
Privet	*Ligustrum*	Shrub	3	N
Red Sesbania	*Sesbania punicea*	Shrub	3	N
Spiny Splinter-bean	*Adenopodia spicata*	Shrub	3	Y
Stink Bean	*Paraserianthes lophantha*	Shrub/Tree	3	N
Sweet Briar (Rose)	*Rosa rubiginosa*	Shrub	3	N

Table 11. The final land-use/land-cover key for the fieldwork in the uMzimvubu, with a total of 4811 points for the 15 classes.

Hex Code	#	Class	Points	Description
#ffff00	1	Irrigated Agriculture	318	Irrigated farmland and pastureland
#FEE238	2	Dryland Agriculture	301	Non-irrigated farmland and grazing-land
#783f04	3	Maize	401	Maize crop (non-irrigated)
#a8a800	4	Grassland	403	Natural grasslands
#6aa84f	5	Indigenous Bush	533	Dominated by *Vachellia sieberiana, Aleo spp.* and *Dovyalis spp.*
#0a14f9	6	Water	300	Waterbodies
#08f3e4	7	Wetland	314	Natural wetlands
#ffffff	8	Bare Ground	302	Quarries, rock, gravel roads, roads, mining, gullies
#000000	9	Urban	300	Built-up areas, infrastructure, roads, rural settlements
#eea2ad	10	Silver Wattle	388	*Acacia dealbata*
#cd6090	11	Black/Green Wattle	328	*Acacia meansii*
#674EA7	12	Poplar	59	*Populus spp.*
#fd0618	13	Pine	379	*Pinus spp.*
#F91DF9	14	Gum	356	*Eucalyptus spp.*
#741b47	15	Other Invasive Alien Plants	129	*Salix spp., Acacia ducurrens, Caesalpinia decapetala, Robinia pseudoacacia and Rubus spp.*

4.4.2. In-field invasive alien plant observations

Acacia dealbata (Silver Wattle) was the most common invader in the catchment. It was found both on hillslopes and along rivers. Isolated dense stands were found within rural communities. *Acacia mearnsii/Acacia decurrens* (Black/Green Wattle) was also very common in the catchment, anecdotally appearing to be less prevalent than Silver Wattle. In some instances, Black/Green Wattle and Silver Wattle co-occur and there is the possibility of hybridization. Additionally, in the south-western part of the catchment, stands of *Acacia decurrens* (Green Wattle) were also found. *Eucalyptus* spp. (gum) form isolated stands within rural communities or in grasslands and appear relatively contained relative to the wattle. Large gum plantations occur in the south-western and eastern parts of the catchment. The north-eastern part of the catchment had a few old gum plantations that are no longer actively managed. *Pinus* spp. (pines) were only present within plantations with only a few exceptions of scattered individuals. Dense infestations of *Populus* spp. (poplar) were difficult to find in the catchment due to their tendency to invade riparian zones of rivers in long, narrow strips, resulting in few pure pixels for training data collection. A few dense stands were found within commercial forestry plantations.

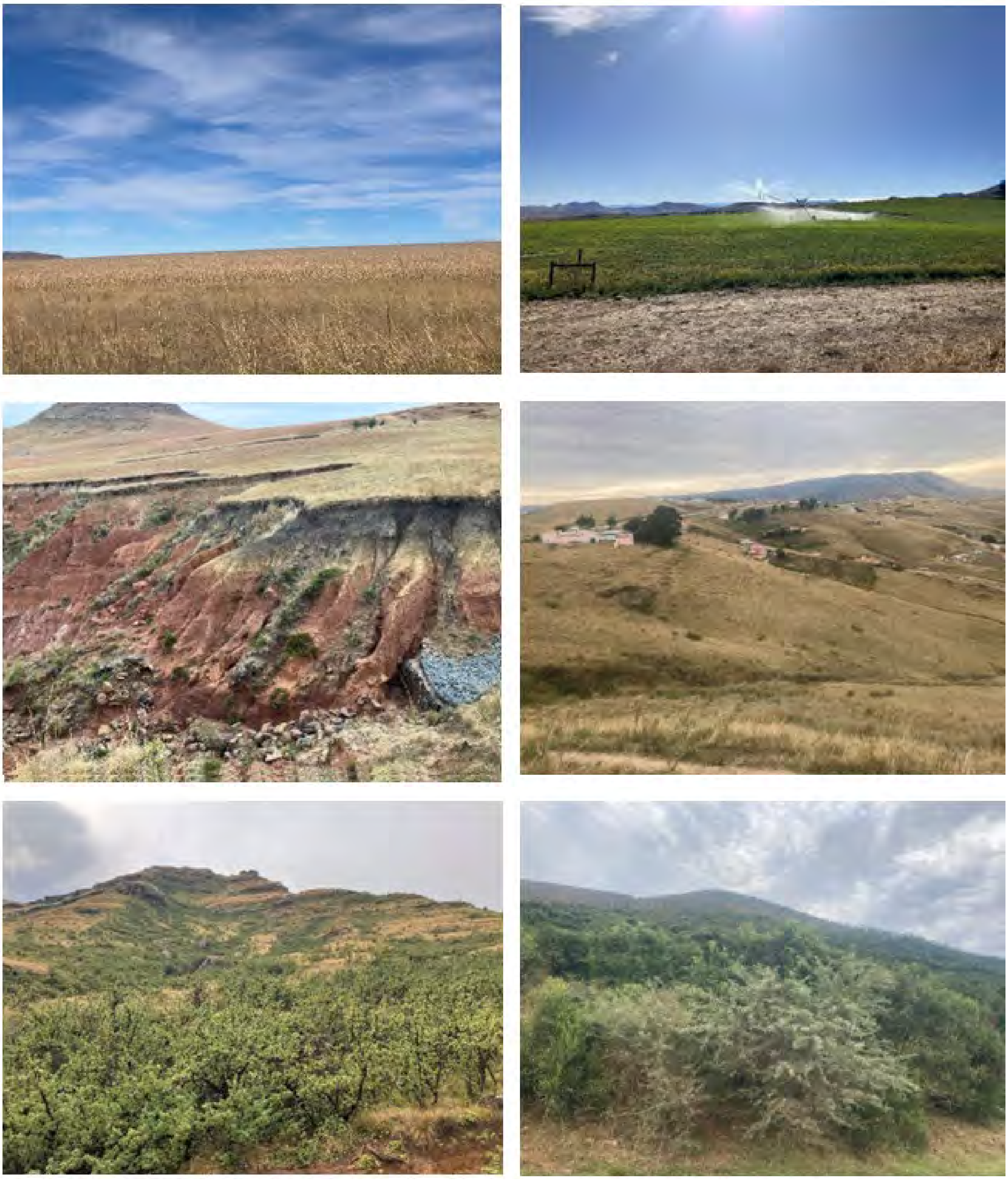


Plate 7. *Photos of landscape and socio-ecological observations in the uMzimvubu Catchment, South Africa. Clockwise from left to right: dryland maize, irrigated agriculture, erosion gullies, a rural community, Ouhoudt on a hillslope, and indigenous bush:* Vachellia spp*.*

Plate 8. *Photos showing characteristic alien plant invasions in the uMzimvubu Catchment, South Africa. Clockwise from top to bottom: Silver Wattle, Black Wattle, Silver Wattle, Black and Silver Wattle mix, dense stands of gums, and a pine plantation in a grassland.*

5. RESULTS AND DISCUSSION

5.1. Woody invasive alien plant occurrence

5.1.1. Luvuvhu Catchment

The best performing classification for the Luvuvhu Catchment was a Random Forest (RF) classifier combining information from 10 Sentinel-2 bands (B2, B3, B4, B5, B6, B7, B8, B8A, B11, B12), 39 indices (**Table S1**, **Table S2**) and data fusion with Advanced Land Observing Satellite (ALOS) global digital surface model (DSM) and landforms datasets (**Figure 10**, **Table S2**, **Figure 11**). Classification results had high accuracy, with 90% overall, and 96% when discriminating alien classes from all non-alien classes (**Table 12**).

Table 12. *This table shows the accuracy results for the classification in the Luvuvhu Catchment. The following accuracies are shown: (i) "Overall" is the accuracy for all classes of the map (n=18), (ii) "IAP Accuracy" refers to the alien classes combined, compared with all other classes combined (n=2), and (iii) "Intra IAP Accuracy" is the accuracy for the invasive alien plant classes only (n=5).*

Statistics			Alien Map (%)
Validation	Overall	Accuracy	90.01
		Kappa	89.38
	IAP Accuracy	Accuracy	96.03
		Kappa	87.23
	Intra IAP Accuracy	Accuracy	94.93
		Kappa	85.04

Results show that invasive alien plants cover over 6% of the Luvuvhu Catchment either in the form of plantation forestry, or alien invasions (**Table 13**). Other Invasive Alien Plants seem to be the most extensive class, covering an estimated 160 km^2. During ground truthing it was observed that this was largely an overestimation, however the location of the invasion was not wrong, rather they occurred at low densities. Pine and gum cover an estimated 47 km^2 and 87 km^2 respectively, the majority (69%) within the strategic water source area.

Table 13. *Estimated area of invasive alien plant invasions and plantations in the Luvuvhu Catchment, and the portion of that catchment that falls into the surface water strategic water source area (SWSA).*

	Invasions + Plantations				Invasions only	
	Catchment		SWSA		Catchment	
Class	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**
Pine	86.7	1.5	83.8	5.1	11.0	0.2
Gum	47.4	0.8	41.5	2.5	19.6	0.3
Lantana	37.3	0.7	24.6	1.5	35.7	0.5
Bugweed	24.8	0.4	20.4	1.2	19.4	0.3
Other	159.7	2.8	76.8	4.7	155.2	2.3
Total	**355.9**	**6.3**	**247.2**	**15.1**	**240.9**	**3.5**

Overall, the classification performed well for pine (**Table 14**). There are some rare instances where the shaded areas of plantation blocks were misclassified as water. Gum classification also had high accuracy, however there are some instances where mature gum invasions (mostly outside of plantations in mountainous areas) are confused with pine. There are also some instances where younger gums are misclassified as orchards. Bugweed classification had reasonable accuracy, particularly in plantation areas, but not as well in more urban areas. *Lantana camara* was often misclassified as the “Alien Other” class where it co-occurs with Triffid weed and Mauritius Thorn. The “Alien Other” class has often been identified in the correct locations by the algorithm, however the footprint of these invasions is often wrong. In some cases the classified areas are too small, and in others, the areas classified are too large. The “Alien Other” class included taxa such as the Castor Oil Plant, Peanut Butter Cassia, Chromolaena, and Mauritius Thorn and these often co-occur with Bugweed and Lantana and as a result end up being confused with these classes.

Table 14. *Ground truthing results for the invasive alien tree map of the Luvuvhu Catchment, South Africa.*

Class	Accuracy	%
Overall	All classes	62.9
	Woody Invasive Alien Plants	66.7
Specific Class Accuracy	Pine	84.9
	Gum	79.0
	Bugweed	63.3
	Lantana	27.7
	Other	51.4

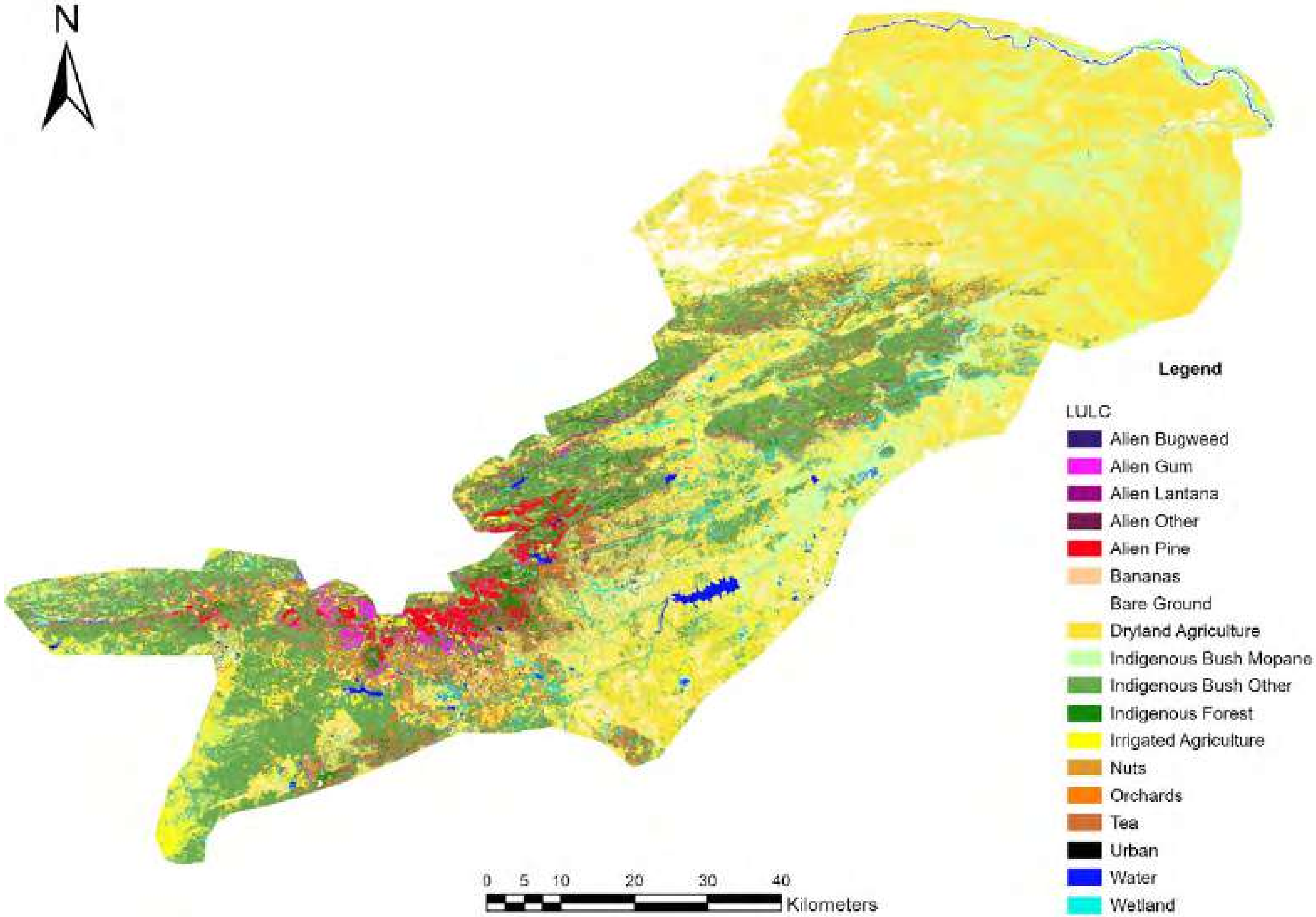


Figure 10. *The woody invasive alien plant map for the Luvuvhu Catchment showing Bugweed, gum, pine, Lantana, and others. An interactive quick look of this available at:* https://mapwaps-luvuvhu.projects.earthengine.app/view/mapwaps-luvuvhu.

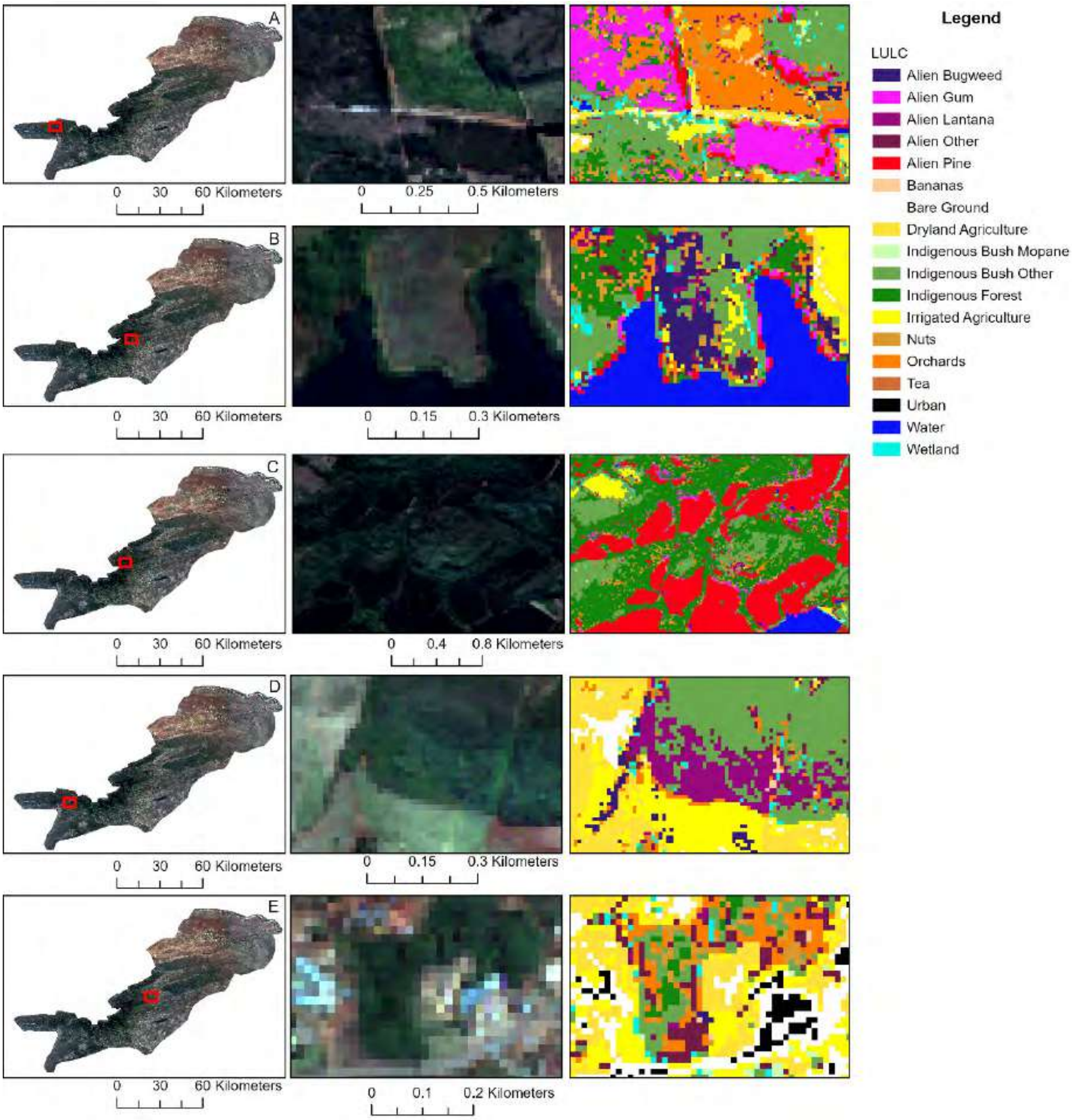


Figure 11. *Classification results for the invasive alien plant taxa in the Luvuvhu Catchment are shown. Each panel shows a specific region of the Luvuvhu Catchment: the Sentinel-2 image and the corresponding classification result. The panels showcase the following: (A) Gum plantation blocks south and west of an orchard in the Soutpansberg; (B) A young Bugweed infestation taking over a recently harvested plantation block in the central regions of the Luvuvhu Catchment (North of the Tate Vondo Dam); (C) Pine plantation stands in between indigenous forest North of the Holy Forest Lake; (D) A dense* Lantana camar*a infestation at the top of a hill bordering irrigated agriculture; (E) Sparsely populated* Chromolaena odorata *and other invasive alien plants growing in a residential area in Thohoyandou.*

The signatures of each of the 18 land-use/land-cover classes (reflectance/wavelength plots) demonstrate which classes are more easily discriminable in general as well as which parts of the spectrum would be more useful to use in discrimination (**Figure 12**). Invasive alien classes tend to have higher red-edge peaks than the native bush, with the exception of indigenous forest. Jitter plots for reflectance ranges for each land-use/land-cover class also offer insights into which bands and indices are most useful for discriminating specific classes (**Figure 13**). For example, B11 (short wave infrared) clearly separates pine and gum from Bugweed, Lantana and other invasive alien plants, whereas B8 (near infrared) separates Bugweed and Lantana.

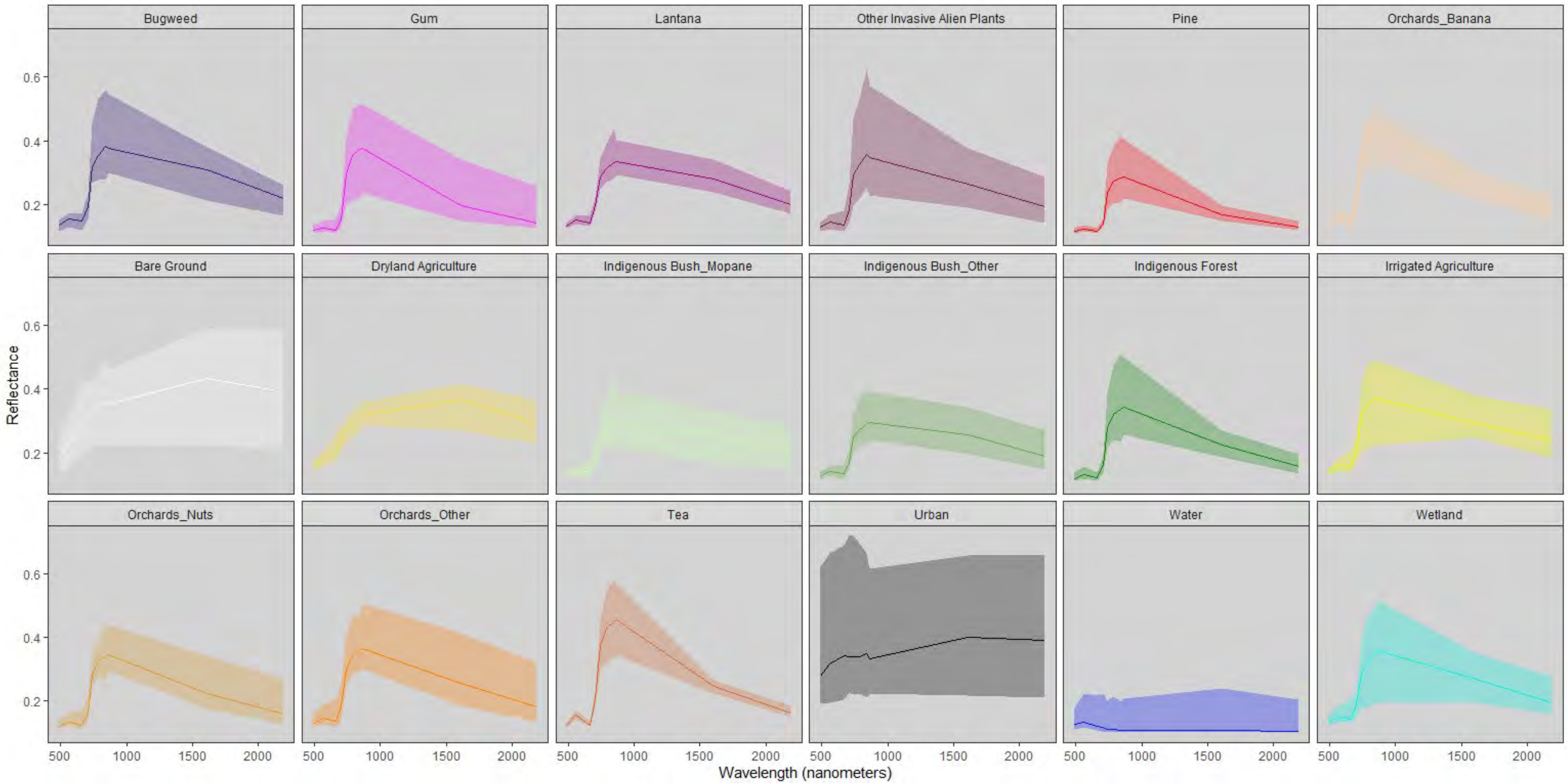


Figure 12. *Line plots showing the range and mean of the spectral signatures for the 18 land-use/land-cover classes generated for the training data for the Sentinel-2 scene acquired for June 2023 for the Luvuvhu Catchment. Bands are connected with lines and should not be confused with the full wave forms, which are more complex.*

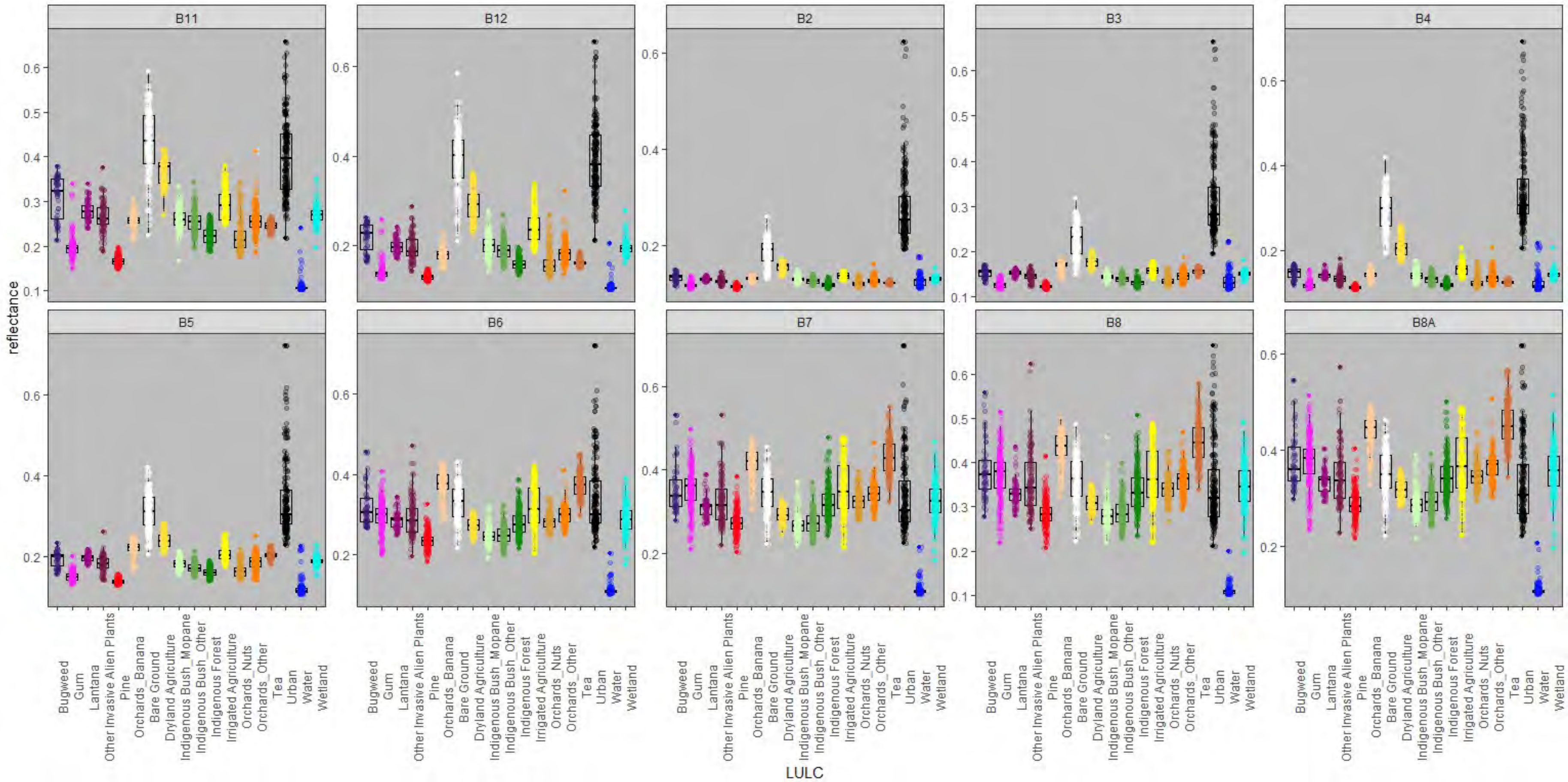


Figure 13. *Jitter plots for all bands included in the classification iterations for invasive alien plants in the Luvuvhu Catchment, South Africa. Plots are shown for each of the key vegetation land-use/land-cover classes generated for the training data for the Sentinel-2 scene acquired for June 2023.*

5.1.2. Sabie-Crocodile Catchment

The best performing classification for the Sabie-Crocodile Catchment was a Gradient Tree Boost (GTB) classifier combining information from 10 Sentinel-2 bands (B2, B3, B4, B5, B6, B7, B8, B8A, B11, B12), 39 indices (**Table S1**, **Table S2**) and data fusion with Advanced Land Observing Satellite (ALOS) global digital surface model (DSM) and landforms datasets (**Figure 14**, **Figure 15**). Classification results had high accuracy, with 88% overall, and 96% when discriminating all alien classes from all non-alien classes (**Table 15**).

Table 15. *This table shows the accuracy results for the classification in the Sabie-Crocodile Catchment. The following accuracies are shown: (i) "Overall" is the accuracy for all classes of the map (n=17), (ii) "IAP Accuracy" refers to the alien classes combined, compared with all other classes combined (n=2), and (iii) "Intra IAP Accuracy" is the accuracy for the invasive alien plant classes only (n=5).*

Statistics			**Alien Map (%)**
Validation	Overall	Accuracy	87.95
		Kappa	87.11
	IAP Accuracy	Accuracy	95.96
		Kappa	89.27
	Intra IAP Accuracy	Accuracy	94.84
		Kappa	87.87

Results show that invasive alien plants cover over 23% of the Sabie-Crocodile Catchment either in the form of plantation forestry, or alien invasions (**Table 16**). Pine and gum cover the largest areas, with an estimated 553 km^2 and 464 km^2 respectively. Bugweed also covers an extensive area of 131 km^2, while it is noted that there may be far more extensive unmapped below canopy invasions that are not detectable by optical satellite remote sensing. Most of the invasion and plantations (96%) is within the strategic water source area.

Table 16. *Estimated area of invasive alien plant invasions and plantations in the Sabie-Crocodile Catchment, and the portion of that catchment that falls into the surface water strategic water source area (SWSA).*

	Invasions + Plantations				**Invasions only**	
	Catchment		**SWSA**		**Catchment**	
Class	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**
Pine	598.0	11.2	597.5	19.1	45.5	0.8
Gum	413.3	7.8	409.5	13.1	33.9	0.6
Bugweed	131.1	2.5	115.2	3.7	66.9	1.2
Lantana	43.4	0.8	31.9	1.0	30.4	0.6
Yellow Bells	20.7	0.4	10.4	0.3	19.7	0.4
Other	38.1	0.7	30.2	1.0	24.1	0.4
Total	**1244.6**	**23.4**	**1194.7**	**38.2**	**220.4**	**4.1**

Pine was classified with high accuracy, but gum less so (**Table 17**). Most of the gum misclassification was for younger plantation blocks, where the signature was confused with orchards, and sometimes Lantana. Given that ground truthing took place a year after training data collection, in some cases new Bugweed infestations had developed within that year, and in other places where Bugweed had previously been recorded, it had been shaded out by growing pine, making it hard to accurately ground truth. For Lantana, one ground truthed stand had high accuracy. The classification of Yellow Bells was surprisingly accurate. However there were some instances where Yellow Bells are mixed among bush and therefore missed at that scale. The "Alien Other" class for this catchment was mainly *Chromoleana*. In this catchment, it was frequently observed interspersed with indigenous bush, which led to under detection. Sometimes this class was also confused with Lantana or Yellow Bells.

Table 17. *Ground truthing results for the invasive alien tree map of the Sabie-Crocodile Catchment, South Africa.*

Class	Accuracy	%
Overall	All classes	68.9
	Woody Invasive Alien Plants	71.4
Specific Class Accuracy	Pine	88.5
	Gum	67.5
	Bugweed	55.5
	Lantana	58.3
	Yellow Bells	54.2
	Other	0.3

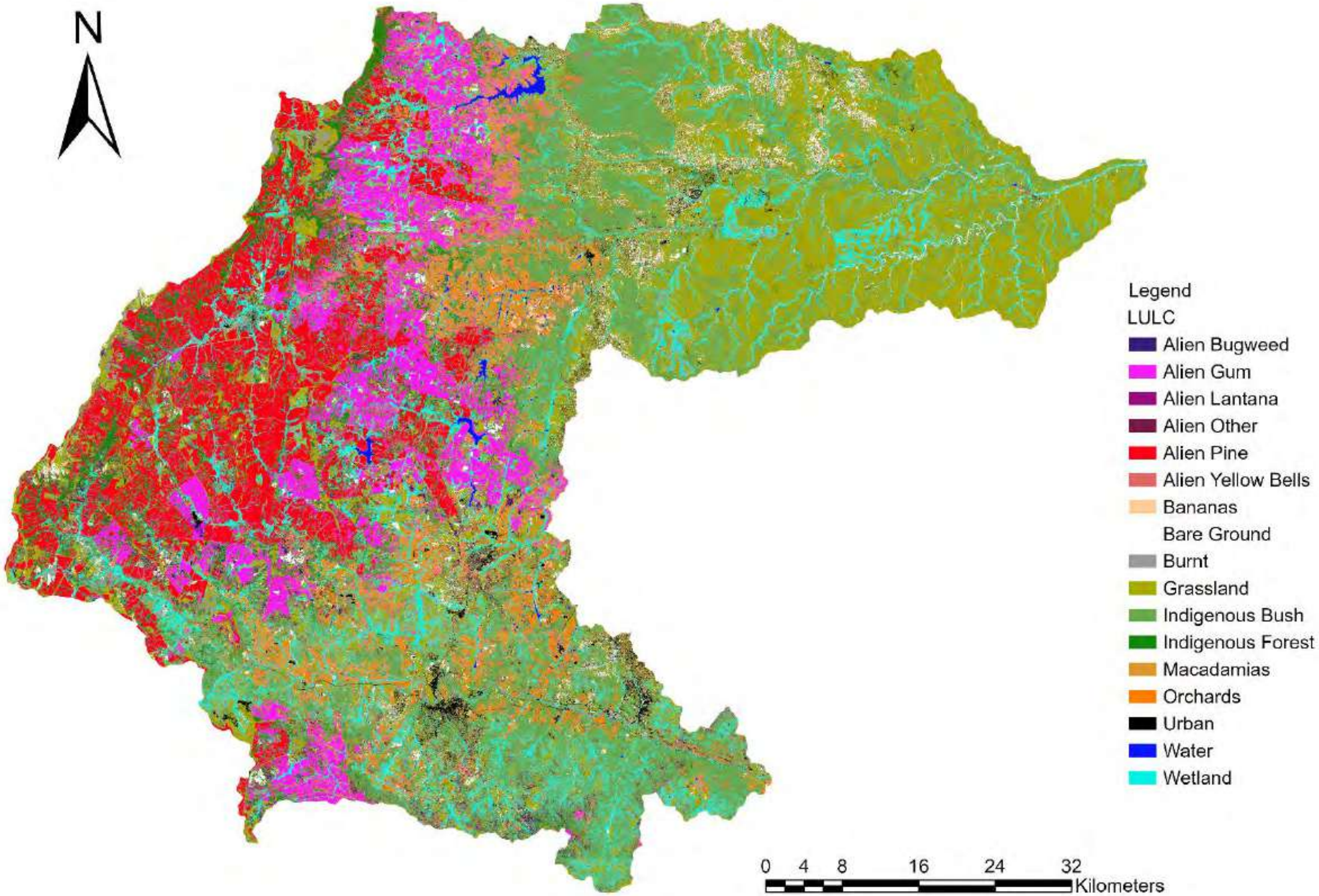


Figure 14. *The invasive alien plant map for the Sabie-Crocodile Catchment showing the location of woody invasive alien plant taxa such as Bugweed, gum, pine, Lantana, Yellow Bells and others. An interactive quick look of this map is available at: https://mapwaps-sabiecroc.projects.earthengine.app/view/mapwaps-sabiecroc.*

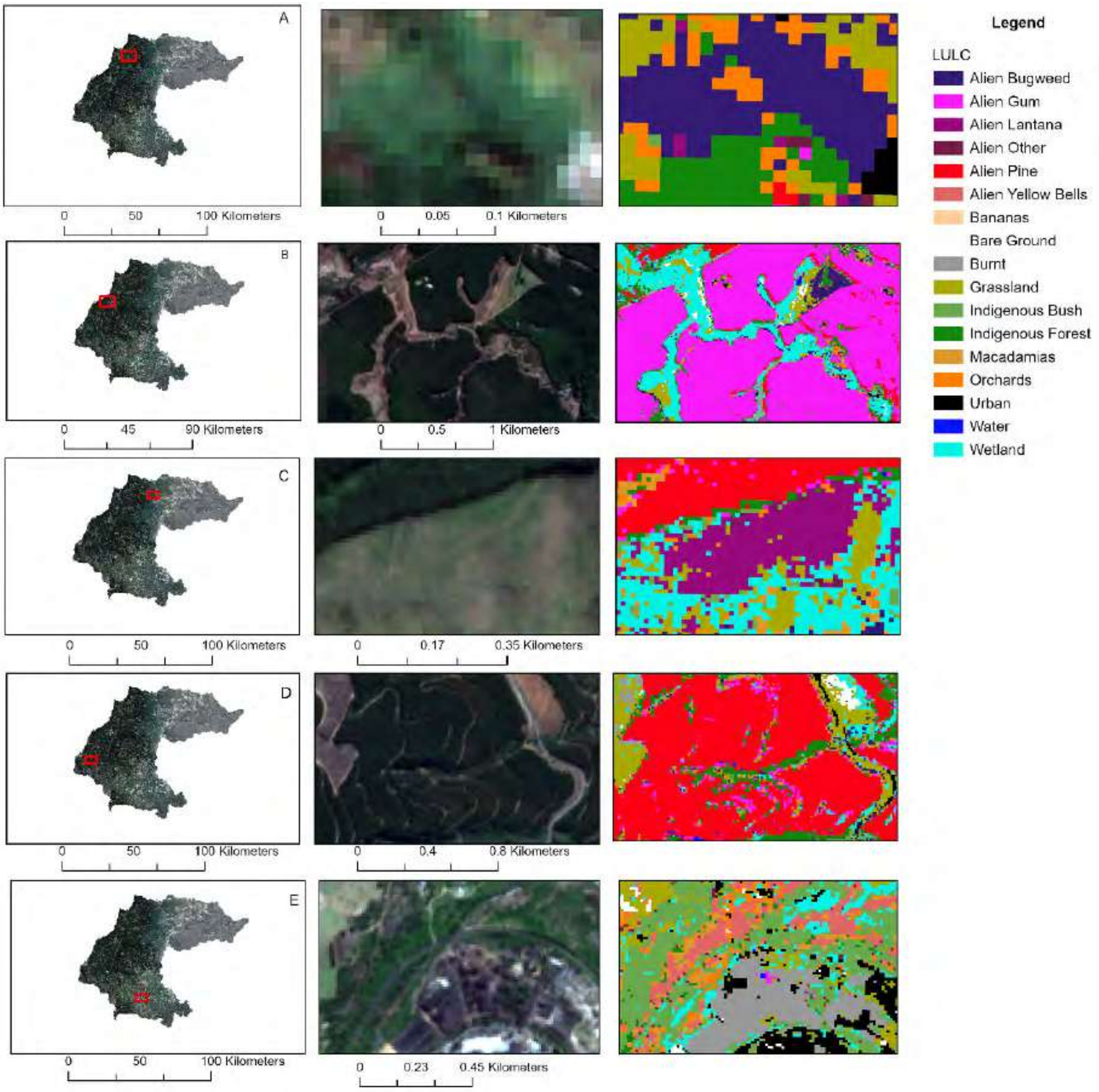


Figure 15. *Classification results for the invasive alien plant taxa in the Sabie-Crocodile Catchment are shown. Each panel displays a specific region of the Sabie-Crocodile Catchment: the Sentinel-2 image and the corresponding classification result. The panels showcase the following: (A) Bugweed infestation at a landfill site; (B) gum plantation in Hazyview; (C) an infestation of Lantana at a timber harvested site in a forestry plantation (D) pine plantations close to Sabie and (E) a dense infestation of Yellow Bells in Mbombela.*

The signatures of each of the 17 land-use/land-cover classes (reflectance/wavelength plots) demonstrate which classes are more easily discriminable in general as well as show which parts of the spectrum would be more useful to use in discrimination (**Figure 16**). Invasive alien classes tend to have higher red-edge peaks than the indigenous bush, grassland and forest. Surprisingly the signatures of the herbaceous invasive alien plants also more closely resemble the invasive alien trees rather than similar growth forms like indigenous grassland and bush. Jitter plots for reflectance ranges for each land-use/land-cover class also offer insights into which bands are most useful for discriminating specific classes (**Figure 17**). For example, B11 (in the short-wave infrared) again clearly separates the invasive alien trees from herbaceous invasive alien plants like Bugweed, Lantana and Yellow Bells, whereas B7 (vegetation red edge) separates Bugweed and Yellow Bells.

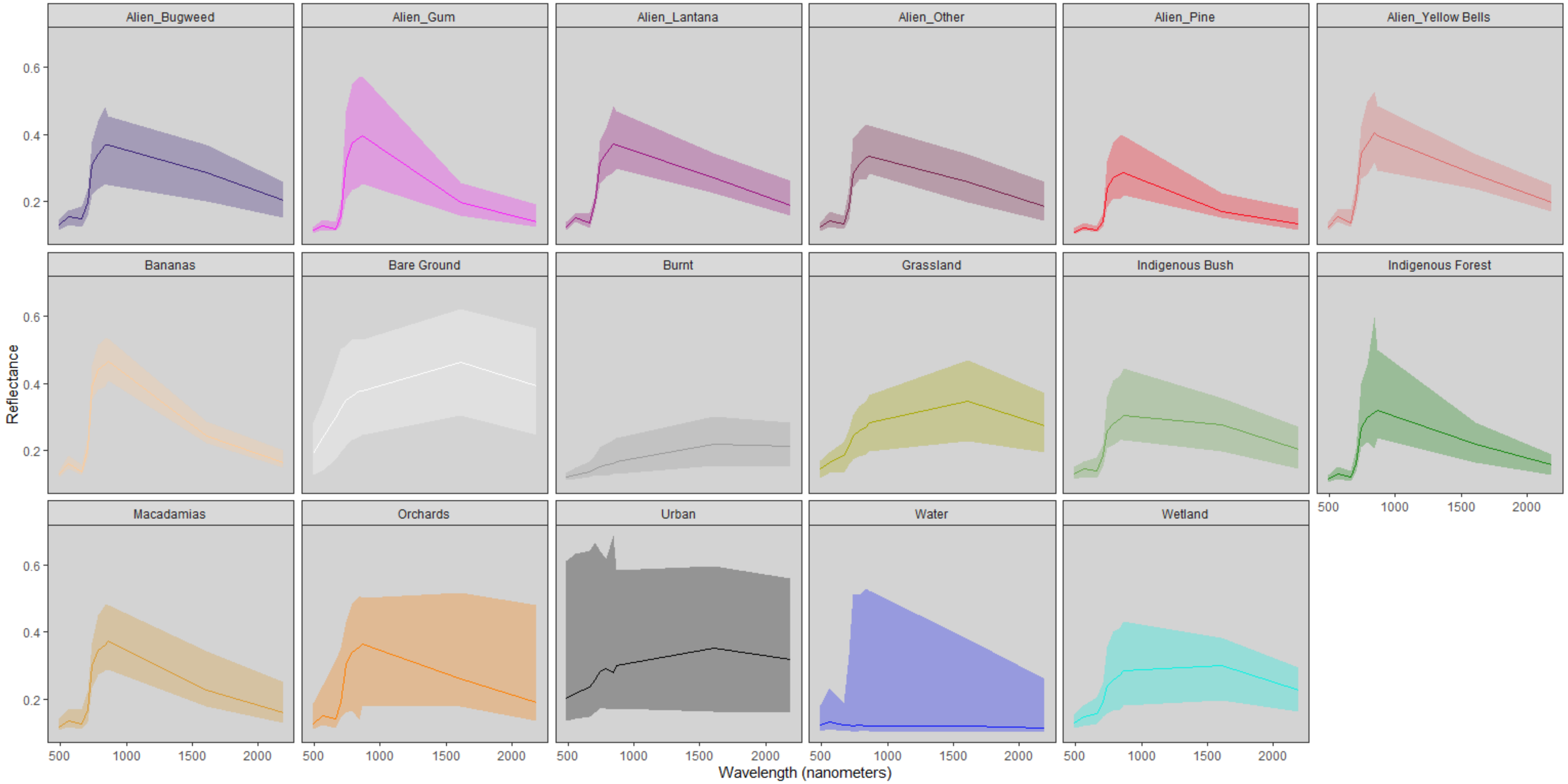


Figure 16. Line plots showing the range and mean of the spectral signatures for the 17 land-use/land-cover classes generated for the training data for the Sentinel-2 scene *acquired for July 2023 for the Sabie-Crocodile Catchment. Bands are connected with lines and should not be confused with the full wave forms, which are more complex.*

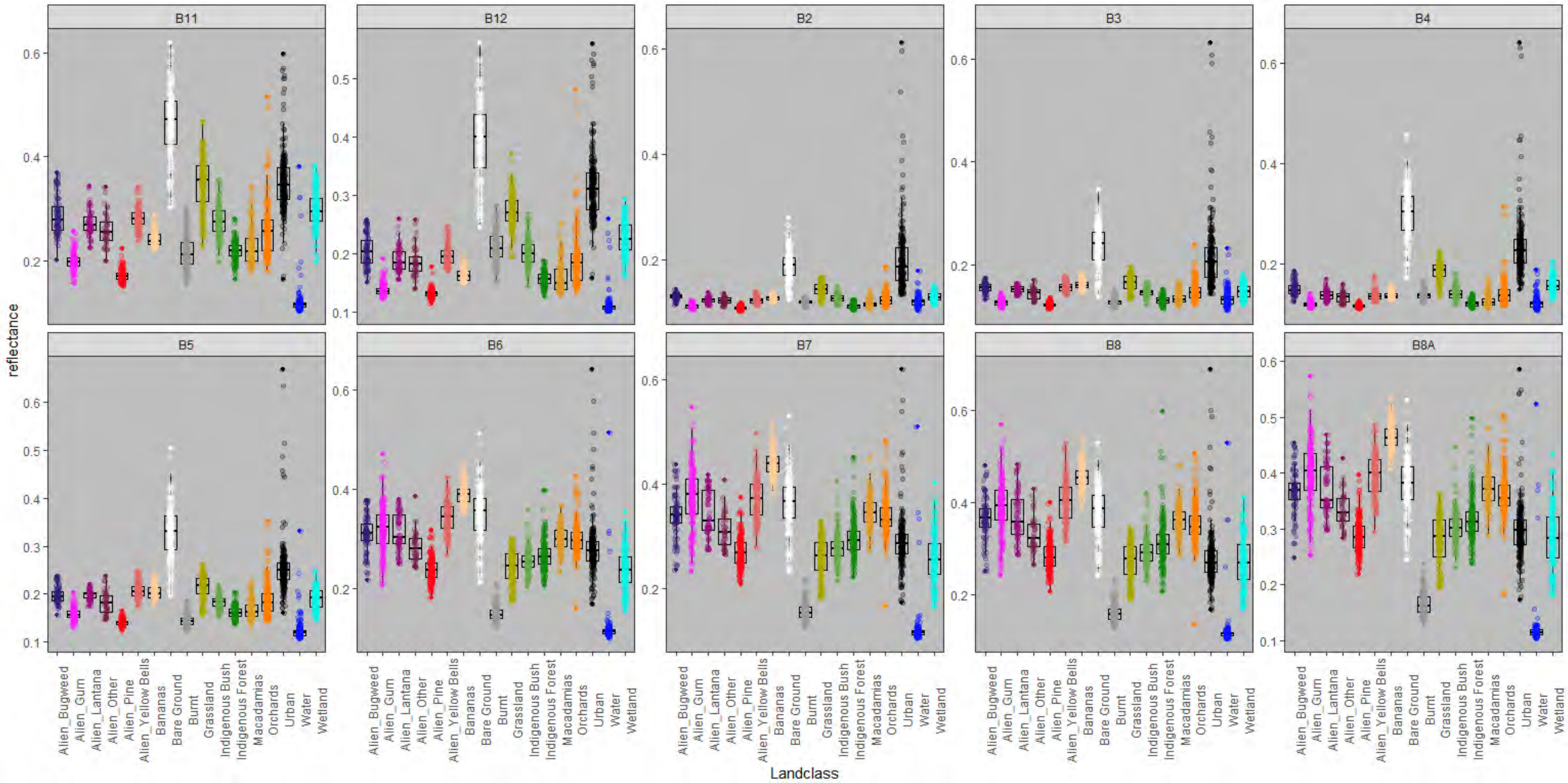


Figure 17. *Jitter plots for all bands included in the classification iterations for invasive alien plants in the Sabie-Crocodile Catchment, South Africa. Plots are shown for each of the key vegetation land-use/land-cover classes generated for the training data for the Sentinel-2 scene acquired for July 2023*

5.1.3. Tugela Catchment

The best performing classification for the Tugela Catchment was a Random Forest (RF) classifier combining information from 10 Sentinel-2 bands (B2, B3, B4, B5, B6, B7, B8, B8A, B11, B12), 39 indices (**Table S1**, **Table S2**) and data fusion with Advanced Land Observing Satellite (ALOS) global digital surface model (DSM) and landforms datasets (**Figure 18**, **Figure 19**). For the Tugela Catchment, classification results had the highest accuracy of all the catchments, with 95% overall, and 98% when discriminating all alien classes from all non-alien classes (**Table 18**).

Table 18. *This table shows the accuracy results for the classification. The following accuracies are shown: (i) "Overall" is the accuracy for all classes of the map (n=17), (ii) "IAP Accuracy" refers to the alien classes combined, compared with all other classes combined (n=2), and (iii) "Intra IAP Accuracy" is the accuracy for the invasive alien plant classes only (n=5).*

Statistics			**Alien Map (%)**
Validation	Overall	Accuracy	94.97
		Kappa	94.64
	IAP Accuracy	Accuracy	97.72
		Kappa	94.03
	Intra IAP Accuracy	Accuracy	96.44
		Kappa	91.79

Results show that invasive alien plants cover over 2% of the Tugela Catchment either in the form of plantation forestry, or alien invasions (**Table 19**). Wattle and gum cover large areas, with an estimated 54 km^2 and 36 km^2 respectively. Poplar invasions are harder to successfully map, as they occur in narrow strips on either sides of rivers, however this project suggests about 40 km^2 invasion of poplar in the Tugela Catchment, bearing this caveat in mind. The majority of the invasion and plantations (80%) fall within the surface water strategic water source area.

Table 19. *Estimated area of invasive alien plants invasions and plantations in the Tugela Catchment and the portion of that catchment that falls into the surface water strategic water source area (SWSA).*

	Invasions + Plantations				**Invasions only**	
	Catchment		**SWSA**		**Catchment**	
Class	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**
Wattle	54.0	0.7	49.6	1.3	42.9	0.6
Pine	6.7	0.1	4.4	0.1	4.5	0.1
Gum	40.4	0.5	38.0	1.0	3.9	0.1
Poplar	12.8	0.2	6.3	0.2	11.1	0.1
Other	35.7	0.5	21.2	0.5	35.3	0.5
Total	**149.6**	**2.0**	**119.5**	**3.1**	**97.7**	**1.3**

Wattle classifications were reasonably accurate overall, however, when invasions are in wetlands and drainage areas, these tend to be misclassified as wetland (**Table 20**). Pine is rather difficult to ground truth due to the scattered nature of invasions in the Drakensberg Mountains, and therefore no polygons were captured. For gums, accuracy was reasonably good, however performed worse in urban areas, and was sometimes easily confused with pine when in riparian zones. Poplar tends to be misclassified as wetlands, as poplar grows densely in wetland systems in the Tugela. The "Alien Other" class only had few polygons (five in total), and therefore is limited by number of samples. This is a challenging class in general, given the large diversity of spectra due to it being a "bin" class. Therefore the purpose was never to achieve high accuracy in and of itself, but to improve the accuracy of the other alien classes by accounting for other more rare taxa in this “bin” class. This is also why it did not receive much attention during ground truthing as a class. However in some cases this bin class was confused with wattle, and in the more arid parts of the catchment, tended to be overestimated, for example around Weenen and Ladysmith.

Table 20. *Ground truthing results for the invasive alien tree map of the Tugela Catchment, South Africa*

Class	Accuracy	%
Overall	All classes	63.4
	Woody Invasive Alien Plants	76.6
Specific Class Accuracy	Gum	66.0
	Pine	88.4
	Poplar	90.2
	Wattle	83.5
	Other	10.0

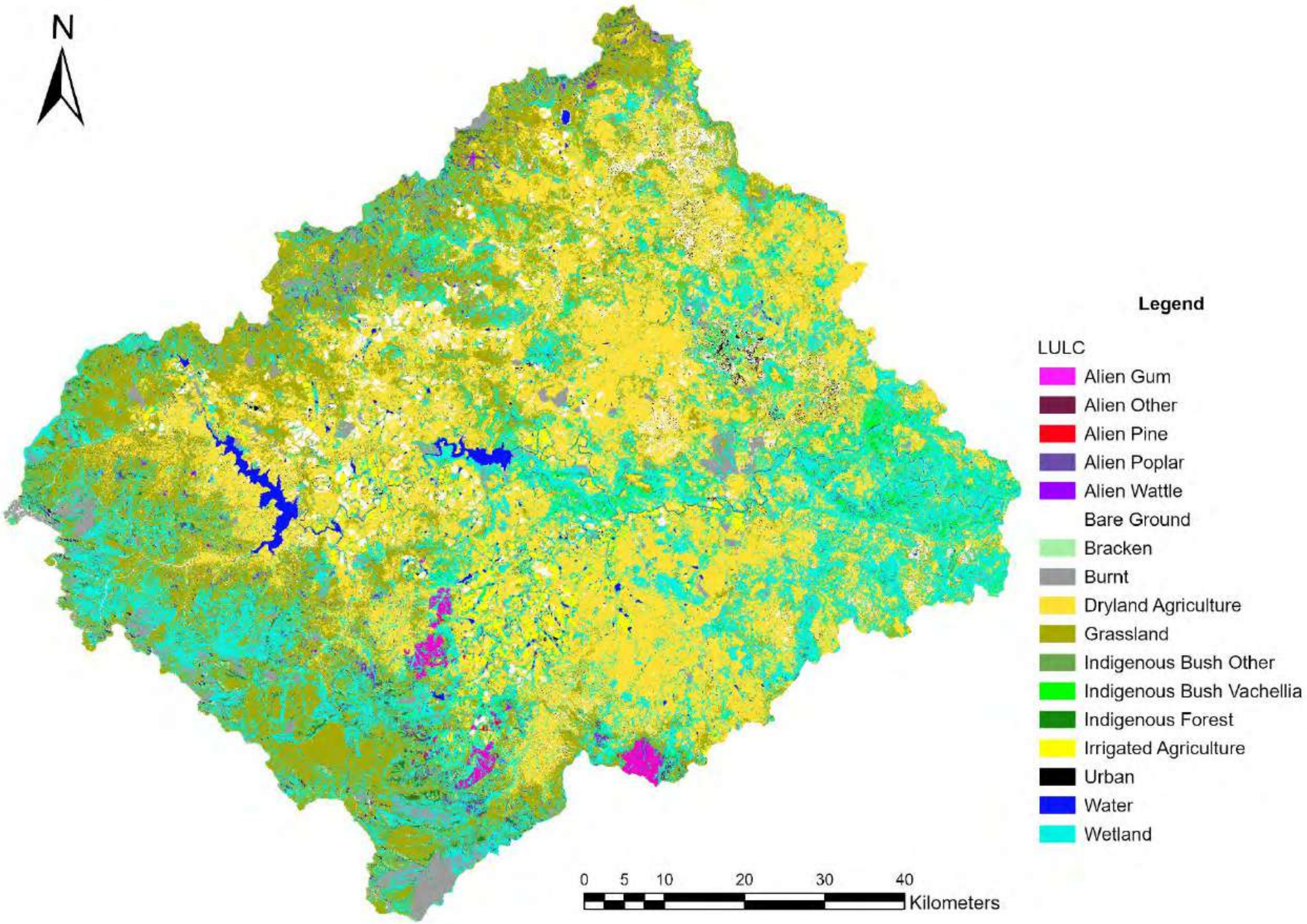


Figure 18. *The invasive alien plant map for the Tugela Catchment showing woody invasive alien plant taxa including classes: Gum, Pine, Poplar, Wattle, and Other Invasive Alien Plants. An interactive quick look of this available at: https://mapwaps-tugela.projects.earthengine.app/view/mapwaps-tugela*

The classification results were highly satisfactory, not only in terms of the accuracy assessments, but also relative to ecological field observations. For example, plantations of invasive alien trees were easily discriminated from adjacent land-use/land-cover classes, while even a small *Robinia pseudoacacia* (Black Locust) infestation growing in a wetland near a farm was detected. Poplar in a wetland near Emmaus was also correctly identified (**Figure 19**).

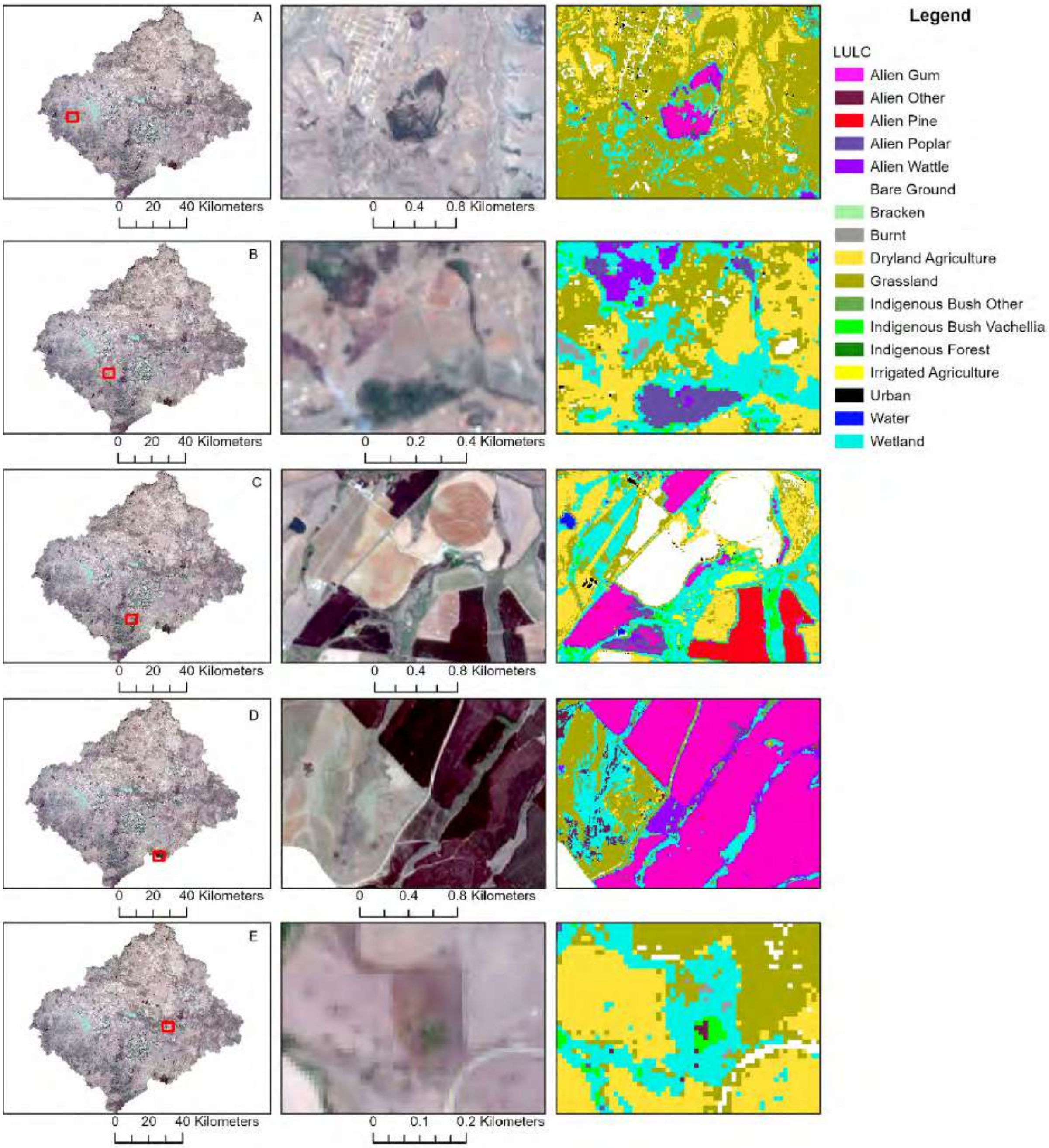


Figure 19. *Classification results for the invasive alien plant taxa in the Tugela Catchment. Each panel displays a specific region of the Tugela Catchment; the Sentinel-2 image and the corresponding classification. The panels showcase the following: (A) An old gum plantation growing in an open grassland next to a community in the western regions of the catchment; (B) A poplar infestation growing in a wetland near Emmaus. A dense wattle thicket grows just north of this poplar infestation; (C) A large pine plantation block growing just east of a gum plantation in the Cathkin Park area; (D) A small block of wattle surrounded by extensive gum plantation blocks near Empangweni; (E) A small* Robinia pseudoacacia *(Black Locust) infestation growing in a wetland near a farm.*

The signatures of each of the 17 land-use/land-cover classes (reflectance/wavelength plots) demonstrate which classes are more easily discriminable in general as well as offer clues as to which parts of the spectrum would be more useful to use in discrimination (**Figure 20**). Invasive alien classes tend to have higher red-edge peaks than the native bush, with the exception of indigenous forest and Vachellia bush. Jitter plots for reflectance ranges for each land-use/land-cover class also offer insights into which bands are most useful for discriminating specific classes (**Figure 21**). For example, B4 (red) and B5 (vegetation red edge) easily discriminated invasive alien taxa from indigenous grasslands and dryland agriculture.

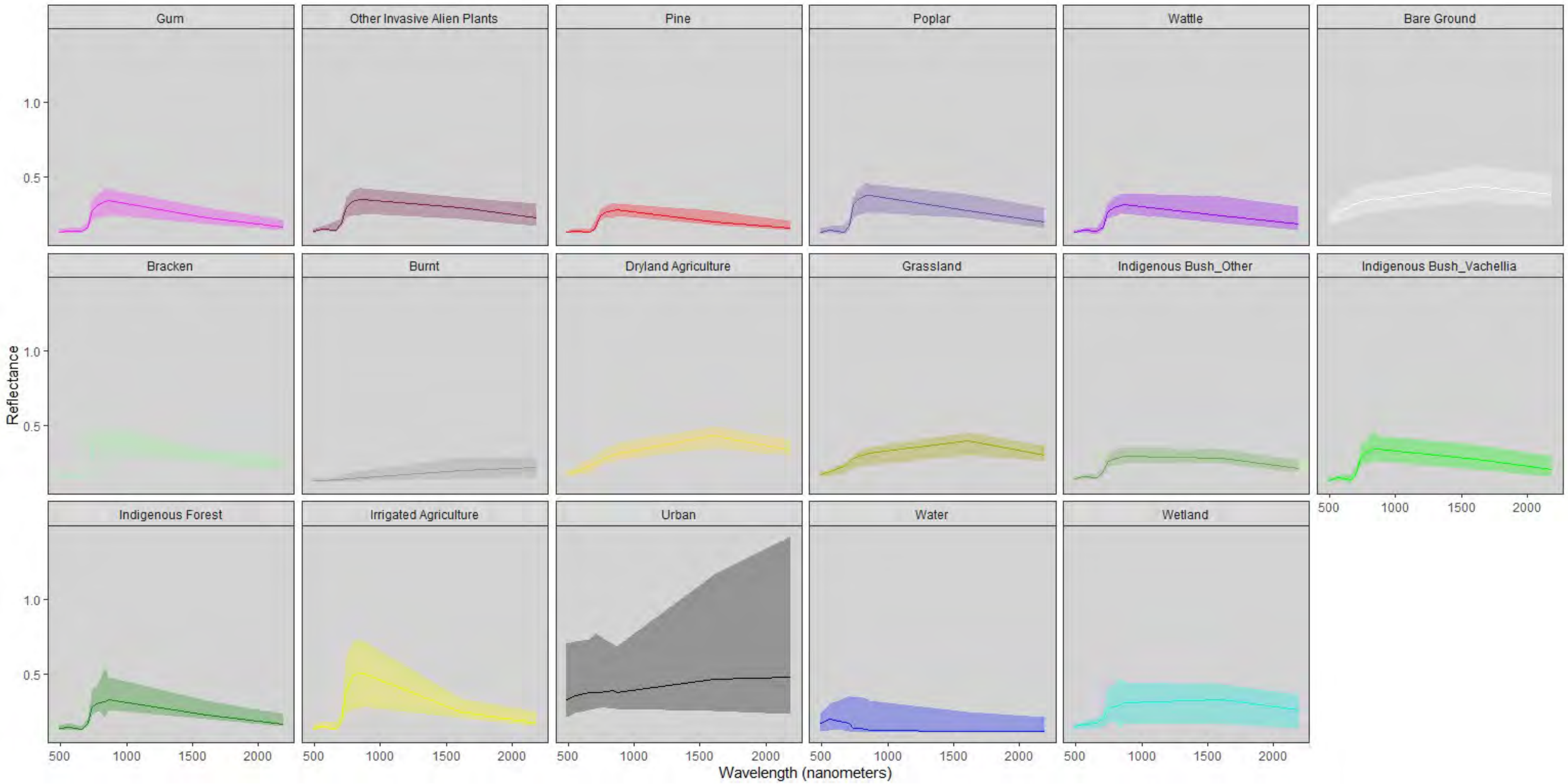


Figure 20. *Line plots showing the range and mean of the spectral signatures for the 17 land-use/land-cover classes generated for the training data for the Sentinel-2 scene acquired for October 2023. Bands are joined with lines and should not be confused with the full wave forms, which are more complex.*

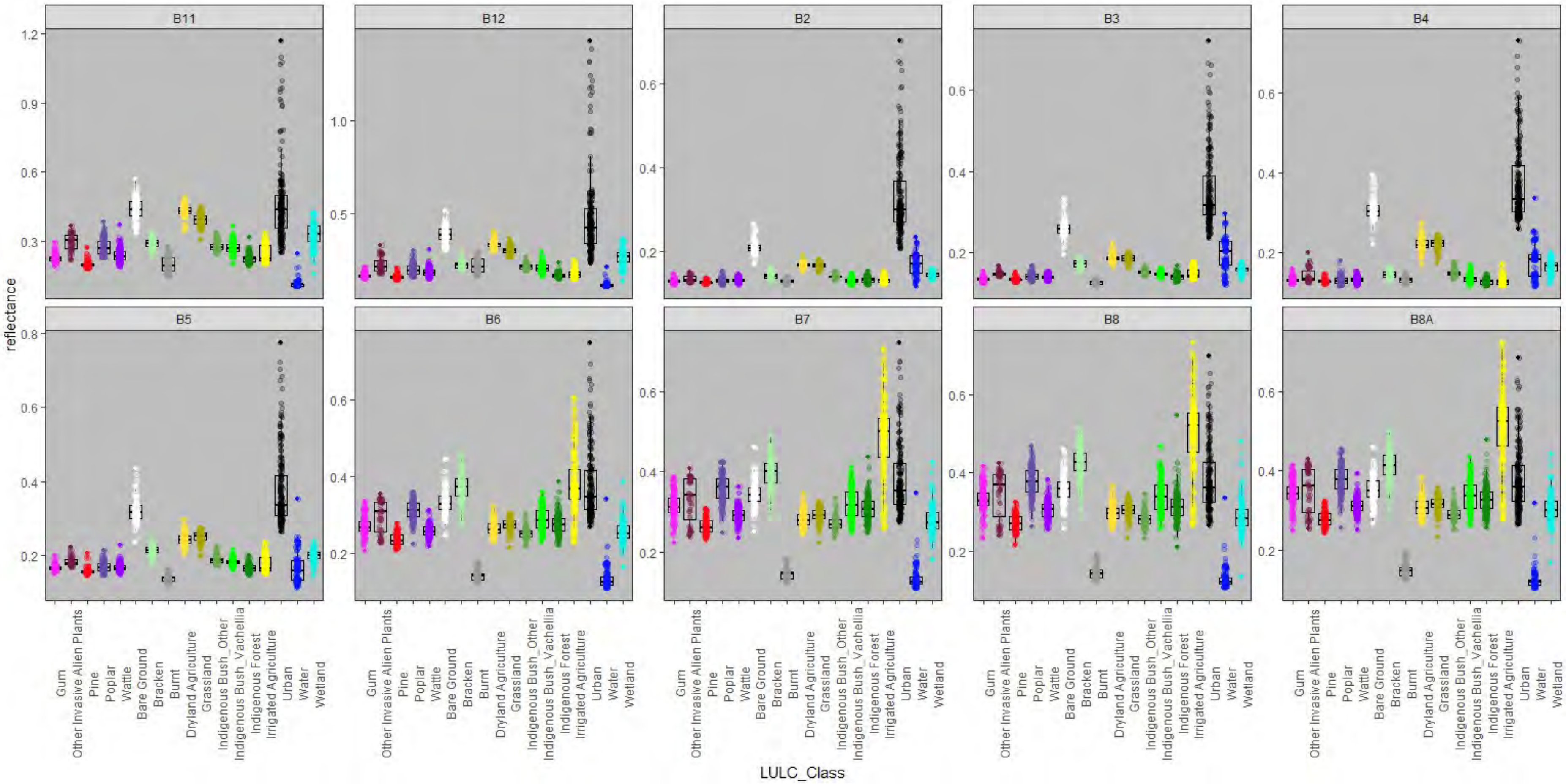


Figure 21. *Jitter plots for all bands included in the classification iterations for invasive alien plants in the Tugela Catchment, South Africa. Plots are shown for each of the key vegetation land-use/land-cover classes generated for the training data for the Sentinel-2 scene acquired for October 2023.*

5.1.4. uMzimvubu Catchment

The best performing classification for the uMzimvubu Catchment was a Random Forest (RF) classifier combining information from 10 Sentinel-2 bands (B2, B3, B4, B5, B6, B7, B8, B8A, B11, B12), 39 indices (**Table S1**, **Table S2**) and data fusion with Advanced Land Observing Satellite (ALOS) global digital surface model (DSM) and landforms datasets (**Figure 23**, **Figure 24**). For the uMzimvubu Catchment, classification results had high accuracy, with 87% overall, and 97% when discriminating all alien classes from all non-alien classes (**Table 21**).

Table 21. *This table shows the accuracy results for the classification. The following accuracies are shown: (i) "Overall" is the accuracy for all classes of the map (n=15), (ii) "IAP Accuracy" refers to the alien classes combined, compared with all other classes combined (n=2), and (iii) "Intra IAP Accuracy" is the accuracy for the invasive alien plant classes only (n=6).*

Statistics			**Accuracy**
Validation	Overall	Accuracy	86.85
		Kappa	85.77
	IAP Accuracy	Accuracy	97.43
		Kappa	94.20
	Intra IAP Accuracy	Accuracy	94.22
		Kappa	89.12

Results show that invasive alien plants cover over 7% of the uMzimvubu Catchment either in the form of plantation forestry, or alien invasions, but mostly the latter (**Table 22**). Silver and Black/Green Wattle cover the largest areas of the catchment, estimated at 485 km^2 and 329 km^2 respectively. Gum and pine are also prolific invaders in the catchment. Most of the invasion (68%) is within the surface water strategic water source area of the catchment.

Table 22. *Estimated area of invasive alien plants invasions and plantations in the uMzimvubu Catchment and the portion of that catchment that falls into the surface water strategic water source area (SWSA).*

	Invasions + Plantations				**Invasions only**	
	Catchment		**SWSA**		**Catchment**	
Class	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**
Silver Wattle	485.2	2.4	279.6	2.5	441.5	2.2
Black/Green Wattle	328.7	1.7	186.8	1.7	280.5	1.4
Gum	288.6	1.5	236.0	2.1	122.3	0.6
Pine	206.5	1.0	185.4	1.6	48.4	0.2
Poplar	56.4	0.3	41.5	0.4	50.4	0.3
Other	35.4	0.2	26.6	0.2	26.6	0.1
Total	**1400.7**	**7.1**	**955.9**	**8.5**	**969.7**	**4.9**

Silver Wattle and Black/Green Wattle had the highest accuracies, followed by gum and then pine (**Table 23**, **Figure 22**). Windbreaks (i.e. thin rows of gums) are often misclassified as wetlands and maize. For poplar, the results are only for three polygons, which are long, thin riparian invasions and are confused with wetlands, the system they typically invade.

Table 23. *Ground truthing results for the invasive alien tree map of the uMzimvubu Catchment, South Africa.*

Class	Accuracy	%
Overall	All classes	73.3
	Woody Invasive Alien Plants	74.8
Specific Class Accuracy	Gum	74.1
	Pine	72.7
	Poplar	11.8
	Silver Wattle	79.4
	Black/Green Wattle	77.6

Figure 22. *Ground truthing results for the uMzimvubu Catchment, South Africa, as an example of the process. The first row is an example of a Black/Green Wattle stand, the second row is an example of a Silver Wattle invasion, and the last row is an example of a gum plantation, all with three polygons. The first column shows the location of the point, the second is the photo as evidence, and the third is the Sentinel-2 imagery.*

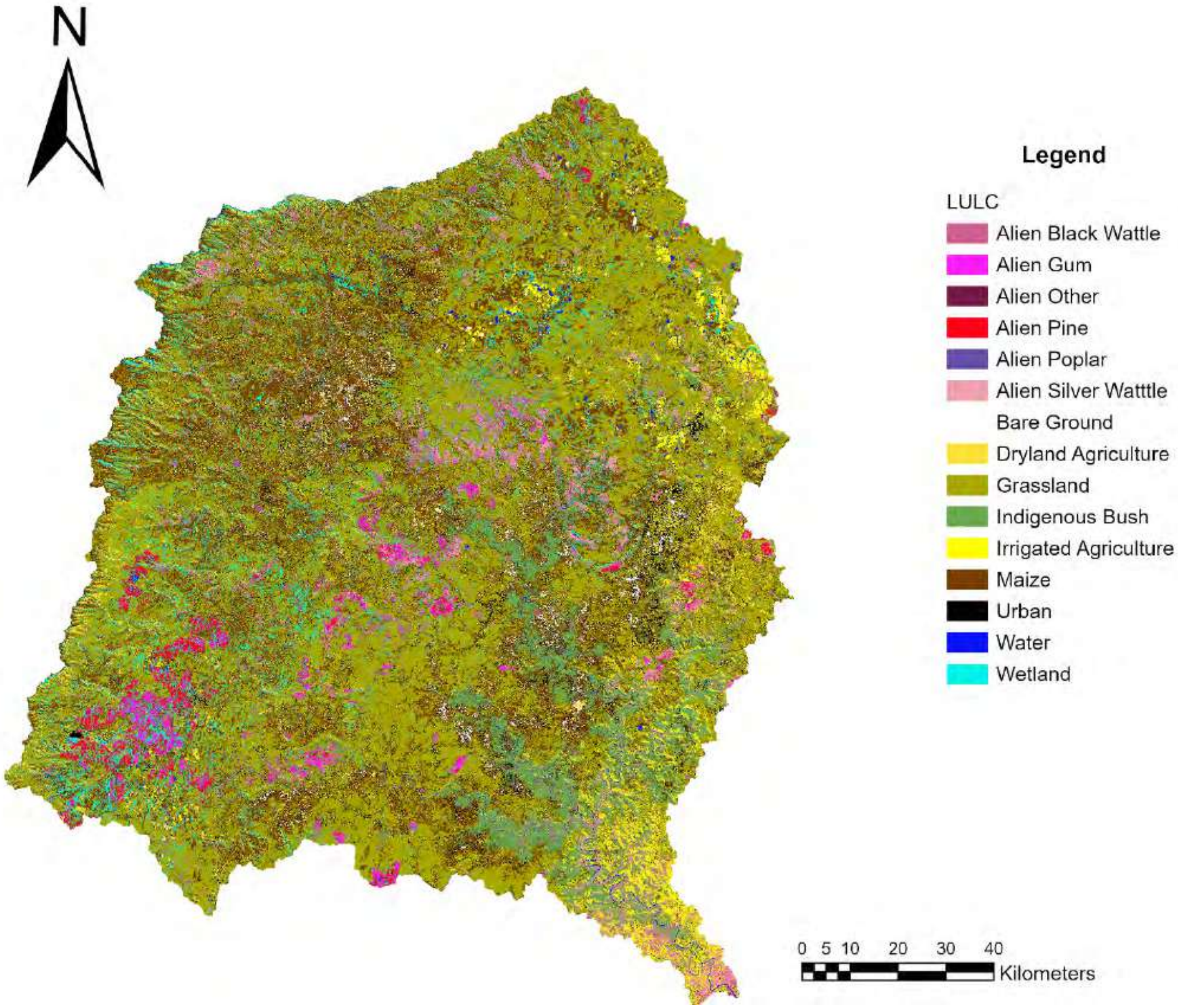


Figure 23. *The invasive alien plant map for the uMzimvubu Catchment showing woody invasive alien plant classes such as Black/Green Wattle, Gum, Pine, Poplar, Silver Wattle and Other Invasive Alien Plants. An interactive quick look of this available at: https://mapwaps-umzimvubu.projects.earthengine.app/view/mapwaps-umzimvubu.*

The classification results were highly satisfactory, not only in terms of the accuracy assessments, but also relative to ecological field observations. Silver and Black/Green Wattle as well as pine and gum plantations were easily discriminated, as well as slivers of poplar invasions along rivers and wetlands (**Figure 24**).

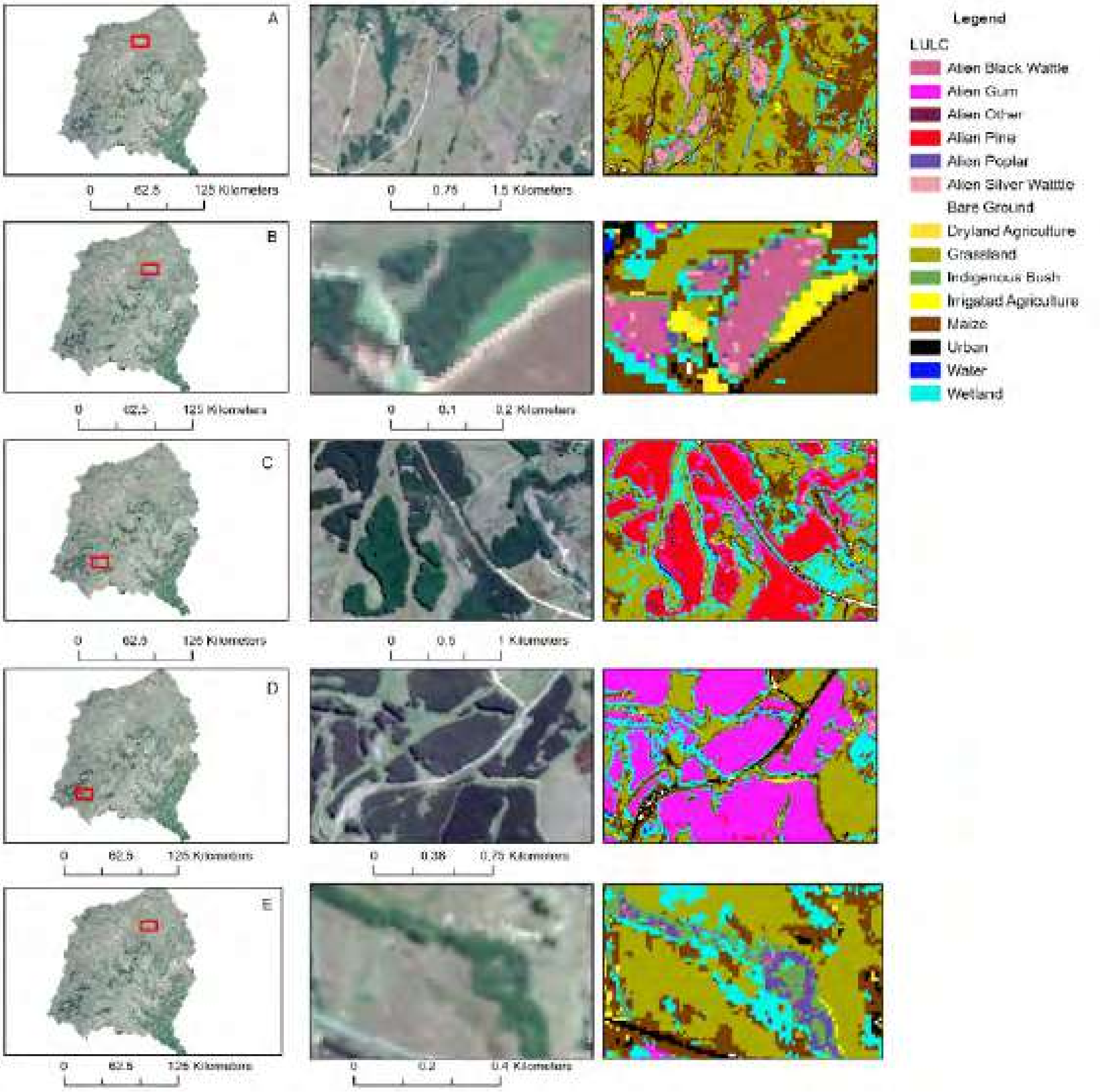


Figure 24. Classification results for the invasive alien plant taxa in the uMzimvubu Catchment are shown. Each panel shows a specific region of the uMzimvubu Catchment; the Sentinel-2 image and the corresponding classification. The panels showcase the following: (A) Silver Wattle blocks in the northern regions of the catchment close to Queens Mercy; (B) a block of Black/Green Wattle infestation growing in a nearby community residential area; (C) pine plantations, (D) gum plantations stands in the southern regions of the catchment; and (E) a narrow band of poplar in Matatiele.

The signatures of each of the 15 land-use/land-cover classes (reflectance/wavelength plots) demonstrate which classes are more easily discriminable in general as well as offer clues as to which parts of the spectrum would be more useful to use in discrimination (**Figure 25**). Invasive alien classes tend to have higher red-edge peaks than the native bush and grassland and even wetlands. Jitter plots for reflectance ranges for each land-use/land-cover class also offer insights into which bands are most useful for discriminating specific classes (**Figure 26**). For example, B11 (in the short wave infrared) easily discriminates poplar from wattle, and B5 (vegetation red edge) discriminates alien taxa from the indigenous land-use/land-cover classes.

Figure 25. *Line plots showing the range and mean of the spectral signatures for the 15 land-use/land-cover classes generated for the training data for the Sentinel-2 scene for the uMzimvubu Catchment acquired for May 2023. Bands are joined with lines and should not be confused with the full wave forms, which are more complex.*

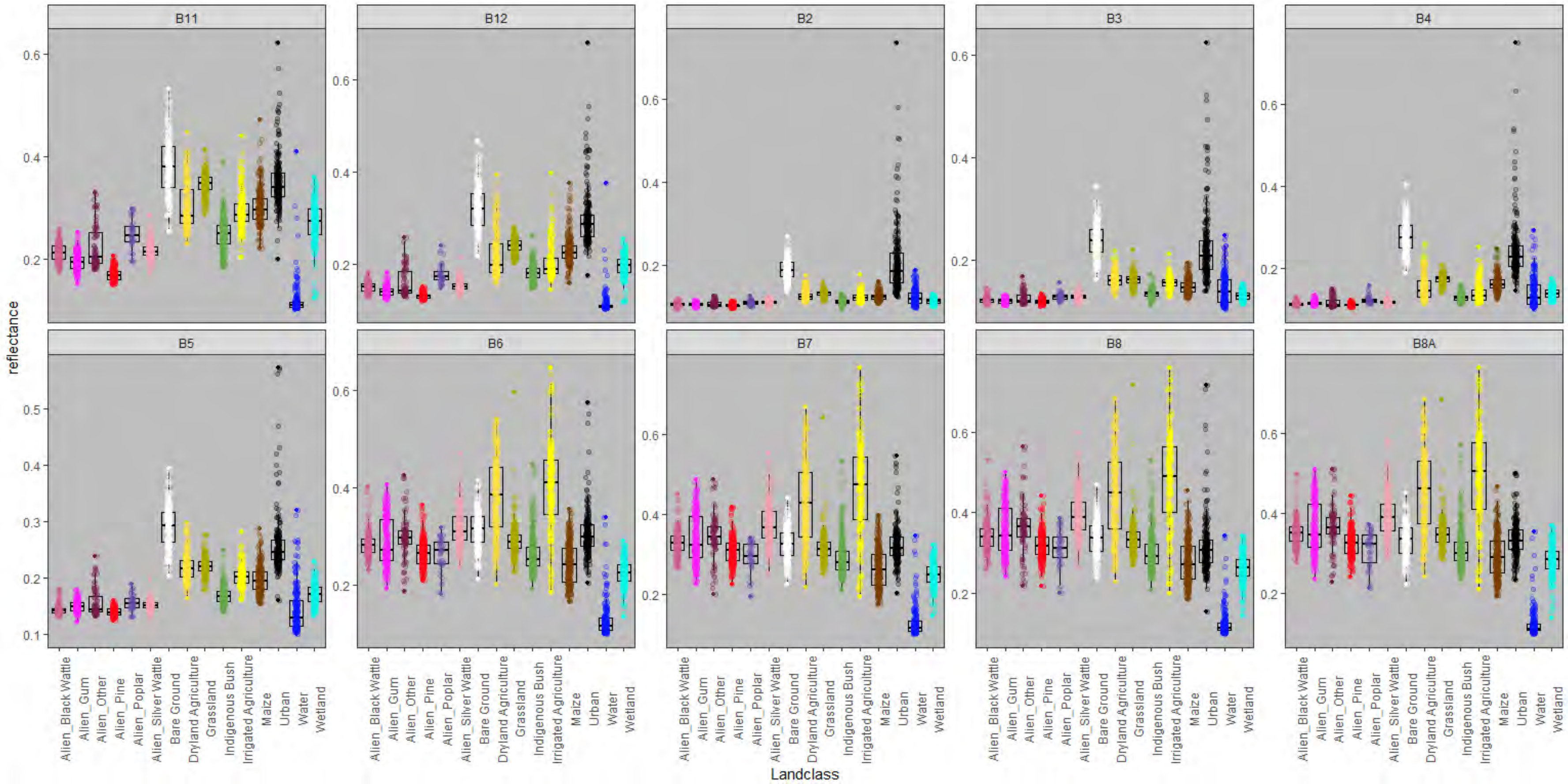


Figure 26. *Jitter plots for all bands included in the classification iterations for invasive alien plants in the uMzimvubu Catchment, South Africa. Plots are shown for each of the key vegetation land-use/land-cover classes generated for the training data for the Sentinel-2 scene acquired for May 2023. The key invasive alien classes: Pine, Gum, Silver Wattle, Black/Green Wattle and Poplar are distinct from other vegetation classes such as Irrigated Agriculture, Grassland and Wetland.*

5.1.5. Comparison with NIAPS

There is a reasonably good correlation between the results of the alien maps produced in this study, and that of the National Invasive Alien Plant Survey (NIAPS - Kotzé et al., 2025) for the four study catchments (R^2 = 0.5) at the catchment scale (**Table 24**, **Figure 27**). This suggests that the catchment level estimates are relatively robust and useful for regional planning and prioritization. However at a finer scale the differences among the two different alien maps are evident (**Figure 28**, **Figure 29**, **Figure 30**, **Figure 31**). An important factor to consider when comparing these maps, is that NIAPS was a survey done at the national scale, which necessarily has a different resolution and purpose. In terms of date, it is our understanding that the NIAPS map is dated somewhere between 2017-23, which should overlap with MAPWAPS to some extent (2023). The NIAPS map shows density in % cover (here displayed as five equal classes with 0-20% hidden) where the MAPWAPS map shows any pixel classified as the class of interest. One of the strengths of the NIAPS map would be the lack of noise, presumably due to processing. This really helps to guide prioritization at a national scale. However, despite this strength, it does seem that using a satellite remote sensing approach yields a result of higher accuracy and precision, for training data that are potentially much cheaper to collect. Therefore, this Water Research Commission funded pilot project has demonstrated its potential for application at a national scale.

Table 24. *The area (km^2) of invasion of woody alien plant invasions (excluding plantations) for the four study catchments, South Africa. N = NIAPS, M = MAPWAPS.*

	Luvuvhu		**Sabie-Croc**		**Tugela**		**uMzimvubu**	
	N	**M**	**N**	**M**	**N**	**M**	**N**	**M**
Gum	52.7	19.6	155.3	33.9	59.4	3.9	237.7	288.6
Bugweed	16.2	19.4	128.0	66.9	40.9	-	179.7	-
Wattle	6.9		45.8	-	190.0	42.9	1329.6	722.0
Pine	7.9	11	90.0	45.5	29.3	4.5	84.7	48.4
Lantana	3.9	35.7	52.8	30.4	5.9	-	29.9	50.4
Poplar	0.0		7.8	-	29.9	11.1	18.6	56.4
Yellow Bells	-		-	19.7	-	-	-	-
Other	-	155.2	-	24.1	-	35.3	-	26.6

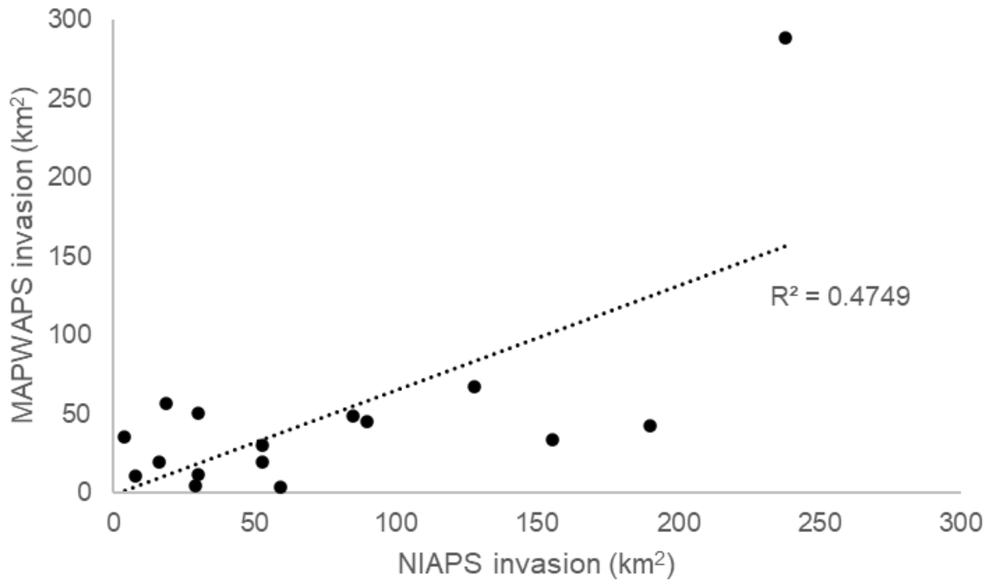


Figure 27. *A comparison between MapWAPS and NIAPS of the area (km²) of invasion of key woody alien plants (gum, Bugweed, wattle, pine, Lantana, poplar) for invasions only(not plantations) for the four catchments (Luvuvhu, Sabie-Crocodile, Tugela, uMzimvubu) in this study.*

In the Luvuvhu Catchment, for some taxa there is relatively good agreement among the two alien maps, however there are errors of commission and omission for the NIAPS data, even when one accounts for plantations which were not included in this map (**Figure 28**).

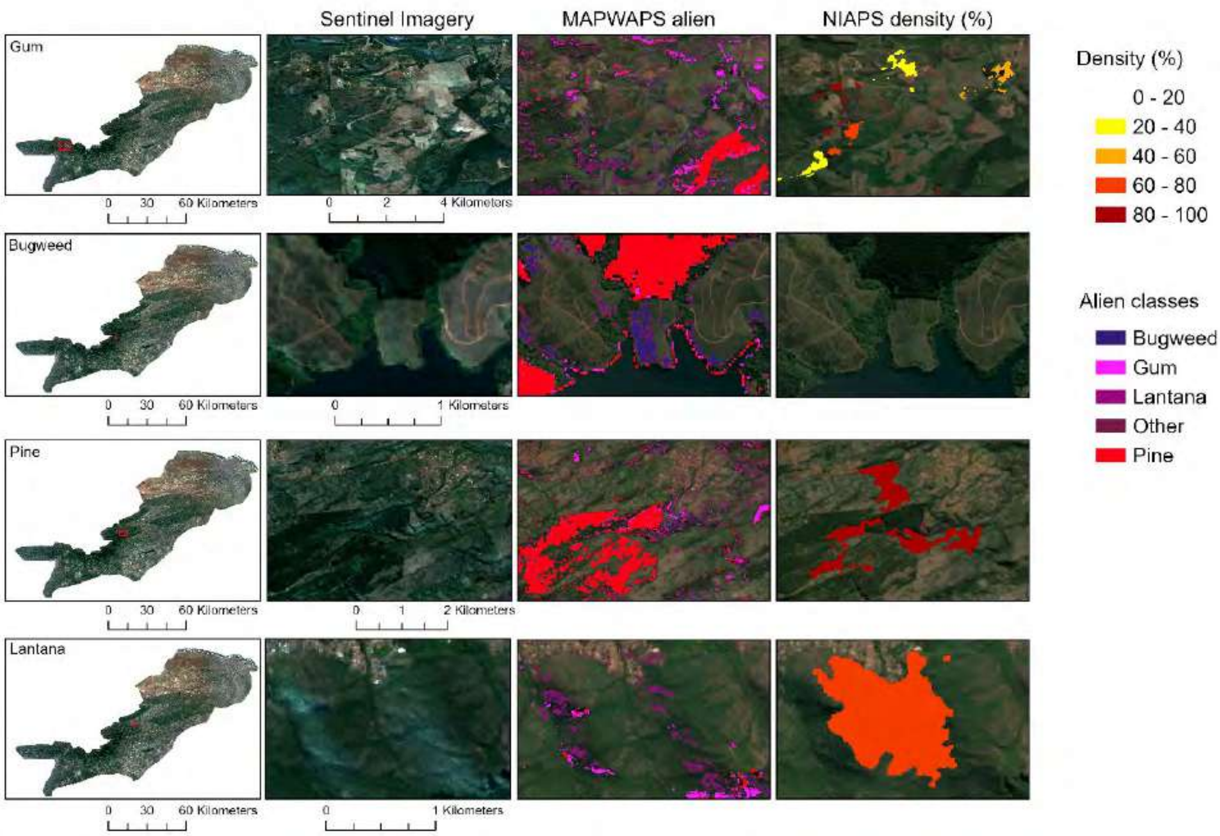


Figure 28. *A comparison between the MAPWAPS woody invasive alien plant maps and NIAPS for a few key taxa in the Luvuvhu Catchment, South Africa. For gum, pine and Lantana, the extent was based on a high density invasion from NIAPS, and for Bugweed, it was based on a known Bugweed invasion from MAPWAPS.*

For Sabie-Crocodile Catchment, we see in one example how Bugweed is located within the vicinity for NIAPS, but the actual invasion not detected in the 20-100% classes (**Figure 29**). Ignoring plantations, there is relatively good agreement for gum and pine invasions. Lantana is not detected at all, the selected scene is an area of ground truthed invasion.

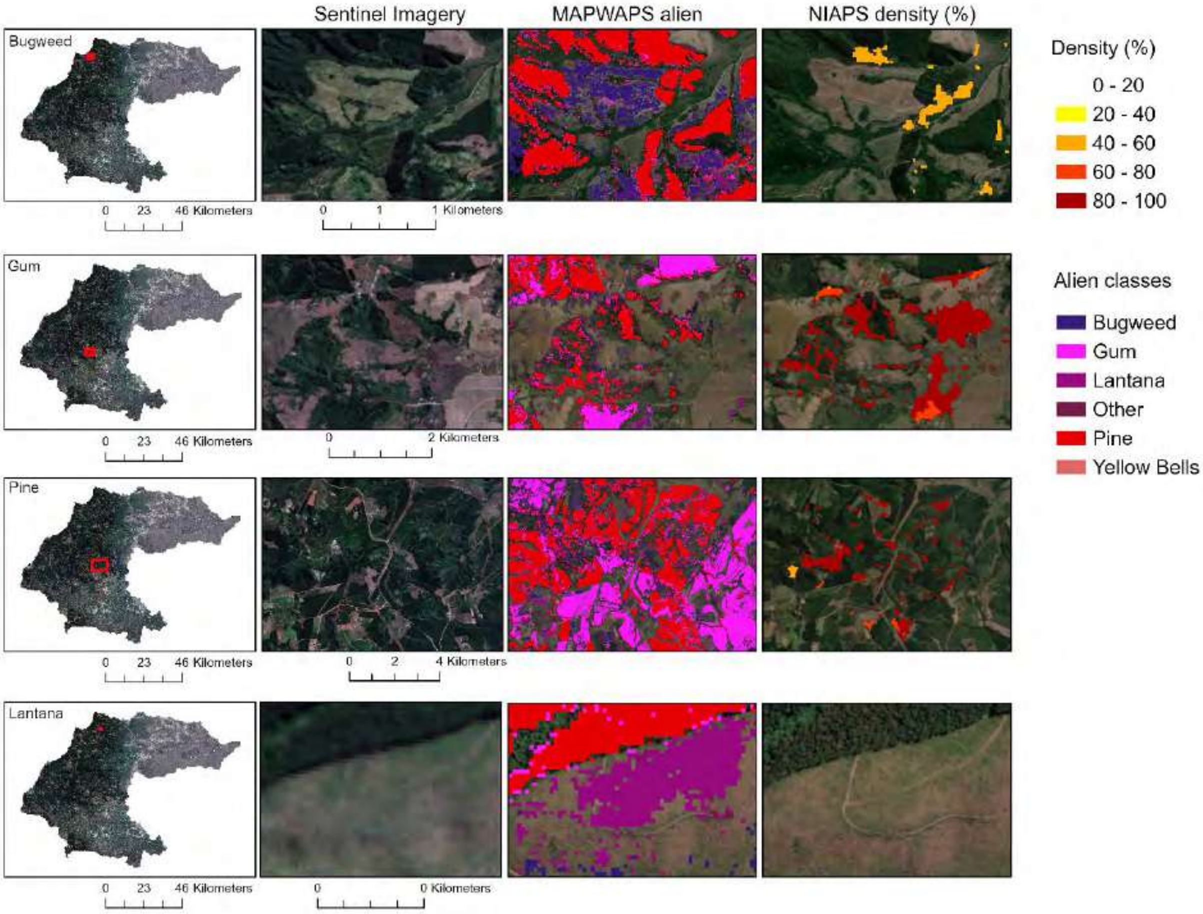


Figure 29. *A comparison between the MAPWAPS woody invasive alien plant maps and NIAPS for a few key taxa in the Sabie-Crocodile Catchment, South Africa. For gum, pine and Lantana, the extent was based on a high density invasion from NIAPS, and for Bugweed, it was based on a known Bugweed invasion from MAPWAPS.*

In the Tugela, one gum invasion is entirely missed, as with poplar, however it is detected in the vicinity, as with pine (**Figure 30**). There is very good agreement with wattle, however instead of being mapped as almost 100% density, it is mapped at 20-60% density.

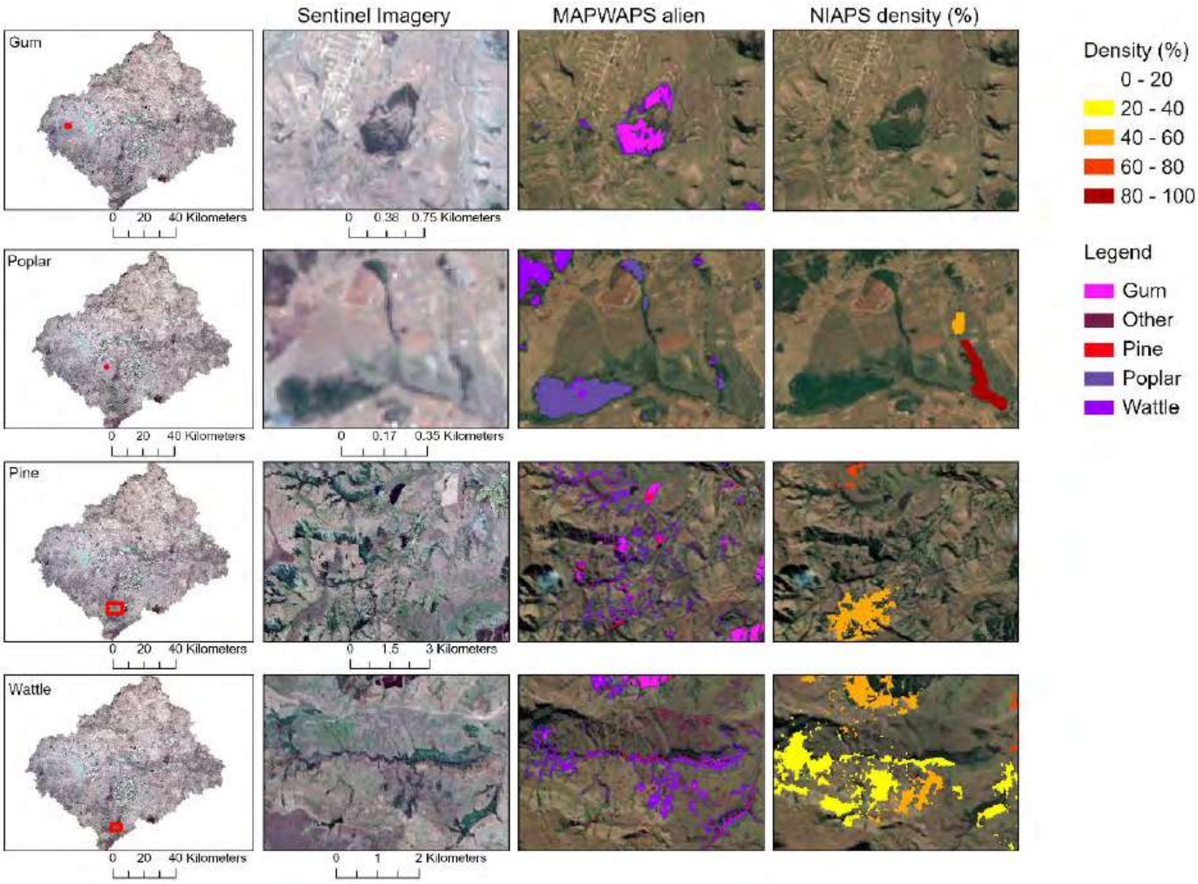


Figure 30. *A comparison between the MAPWAPS woody invasive alien plant maps and NIAPS for a few key taxa in the Tugela Catchment, South Africa. For poplar, pine and wattle, the extent was based on a high density invasion from NIAPS, and for gum, it was based on a known invasion from MAPWAPS.*

In the uMzimvubu Catchment, there is some agreement for Silver Wattle and pine for the selected examples, however not for Black/Green Wattle, though it is detected in the vicinity (**Figure 31**). A dense poplar invasion just outside Matatiele is completely missed.

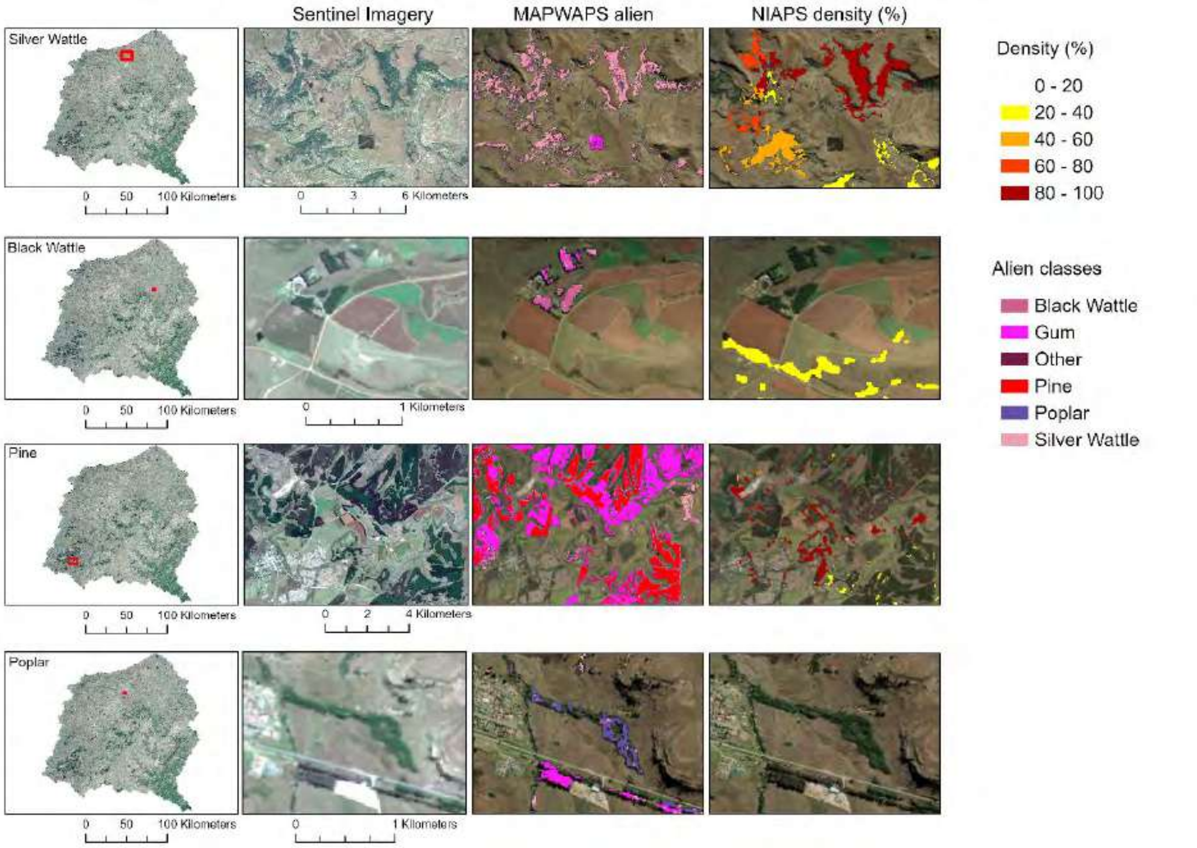


Figure 31. *A comparison between the MAPWAPS woody invasive alien plant maps and NIAPS for a few key taxa in the uMzimvubu Catchment, South Africa. For wattle and pine, the extent was based on high density invasion from NIAPS, and for poplar, it was based on a known invasion from MAPWAPS, just outside Matatiele.*

5.2. Woody invasive alien plant density

This approach to estimate plant density using random forest probability produces spatially accurate results (**Figure 32**). Additionally, it makes sense that pine and gum form dense stands (46-76%) in most catchments, as these are dominated by plantations (**Table 25**). In addition, it is sensible that pines in the Tugela are more sparse, as the invasions in the mountains are of scattered pines, and there are not many pine plantations. The more herbaceous taxa, e.g. Bugweed, Lantana, Yellow Bells and other aliens have much lower densities, which is also what is observed in the field, with many of these taxa growing among native species and seldom forming closed canopy stands over large areas.

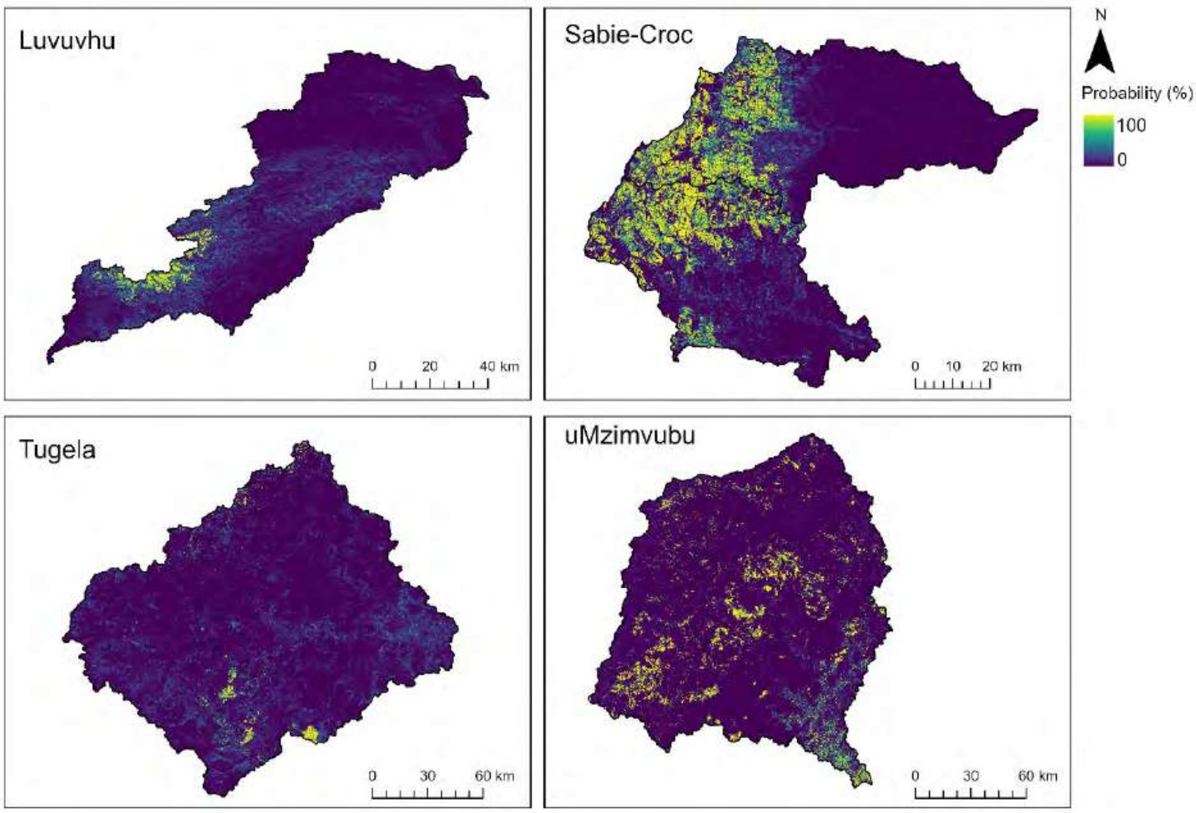


__Figure 32.__ An estimate of vegetation density (percentage cover) based on random forest probability results.

__Table 25.__ The mean ± standard deviation of the density (percentage cover) of woody invasive alien plants in the four different catchments and overall.

	Luvuvhu	**Sabie-Croc**	**Tugela**	**uMzimvubu**	**Mean**
Gum	46 ± 30.4	58 ± 28	69 ± 24.7	46 ± 24.8	**55 ± 27**
Pine	76 ± 23.5	74 ± 23.3	46 ± 25.6	66 ± 25	**65 ± 24.4**
Wattle			37 ± 18.6		**37 ± 18.6**
Black/Green Wattle				41 ± 21.1	**41 ± 21.1**
Silver Wattle				19 ± 12.1	**19 ± 12.1**
Poplar			43 ± 19.4	21 ± 11.3	**32 ± 15.4**
Other	13 ± 8.4	13 ± 9.5	26 ± 16.1	28 ± 17.7	**20 ± 12.9**
Bugweed	36 ± 13.4	21 ± 13.3			**28 ± 13.4**
Lantana	13 ± 19.2	12 ± 9.4			**12 ± 14.3**
Yellow Bells		22 ± 20			**22 ± 20**
Mean	**18.4 ± 9.49**	**20 ± 10.35**	**22.1 ± 10.44**	**22.1 ± 11.2**	**33.1 ± 10.37**

However relating this to field collected data suggests that all three indicators are not readily suitable for density estimation (percentage cover) of woody invasive alien plants (Random Forest, 100 m grid cell, and NDVI approach respectively: R^2 = 0.14, R^2 = 0.38, R^2 = 0.13, **Table 26**, **Figure 33**). Although the 100 m grid cell approach holds the most promise. Part of the issue may be the small validation dataset (and hence low power) as this was not the main purpose of this study. Therefore, the best performing approach may warrant further exploration.

Table 26. *The results of the remote sensing invasive alien plant density method (percentage cover), relative to field notes, for a few examples from all four catchments, South Africa. For photographs of most of the examples below, see* ***Plate 9****.*

Catchment	Class	Coordinates	Details	Field	Random	100m	NDVI
uMzimvubu	Black/Green Wattle	28.8982151; -31.4236621	Mature and dense Black/Green Wattle with an almost complete canopy cover (grasses in	90	99.8	57	0.54
	Pine	28.2888413;-30.9989674	Pine plantation not yet fully mature with 60% canopy cover and grasses showing under-canopy.	60	99.6	100	0.50
Sabie-Crocodile	Pine	30.7608248; -25.1465655	Young pine plantation block, grass visible between pine	70	98.2	82	0.46
	Gum	30.9272805; -25.5502456	Gum infestation/woodlot of different ages; about 70% density can see grass between	80	42.9	24	0.39
	Bugweed	30.9445344; -24.9226828	Bugweed infestation growing in a pine plantation; pines are still young.	60	14.8	72	0.28
Tugela	Wattle	29.0495682; -28.7025561	Moderately sparse wattle infestations of 1-3 m in height.	75	90.6	89	0.37
	Gum	29.6845029; -29.0147474	Dense gum plantation.	100	82.9	81	0.37
Luvuvhu	Bugweed	30.3301815; -22.9370885	Dense Bugweed growing between young pine seedlings.	80	67.8	34	0.35
	Pine	30.1091736; -23.0420349	Dense pine plantation block.	100	98.2	81	0.39
	Other Aliens	30.0522507; -23.1196521	Large single standing *Chromolaena odorata* plants growing among indigenous	30	14.4	6	0.28


Dense Black Wattle infestation in the uMzimvubu Catchment.


Extensive, not fully mature pine plantation in the uMzimvubu Catchment.


Gum woodlot of different ages (3-18 m) in the Sabie-Crocodile Catchment.


Dense *Solanum mauritianum* growing between planted pine seedlings in the Luvuvhu Catchment.


Pine plantation block with full canopy in the Luvuvhu Catchment.


Sparse *Chromolaena odorata* invading indigenous bush in the Luvuvhu Catchment.


Sparse wattle infestations in the Tugela Catchment.


Dense mature gum plantation in the Tugela Catchment.

Plate 9. *Photographic evidence for the examples described in* ***Table 26****.*

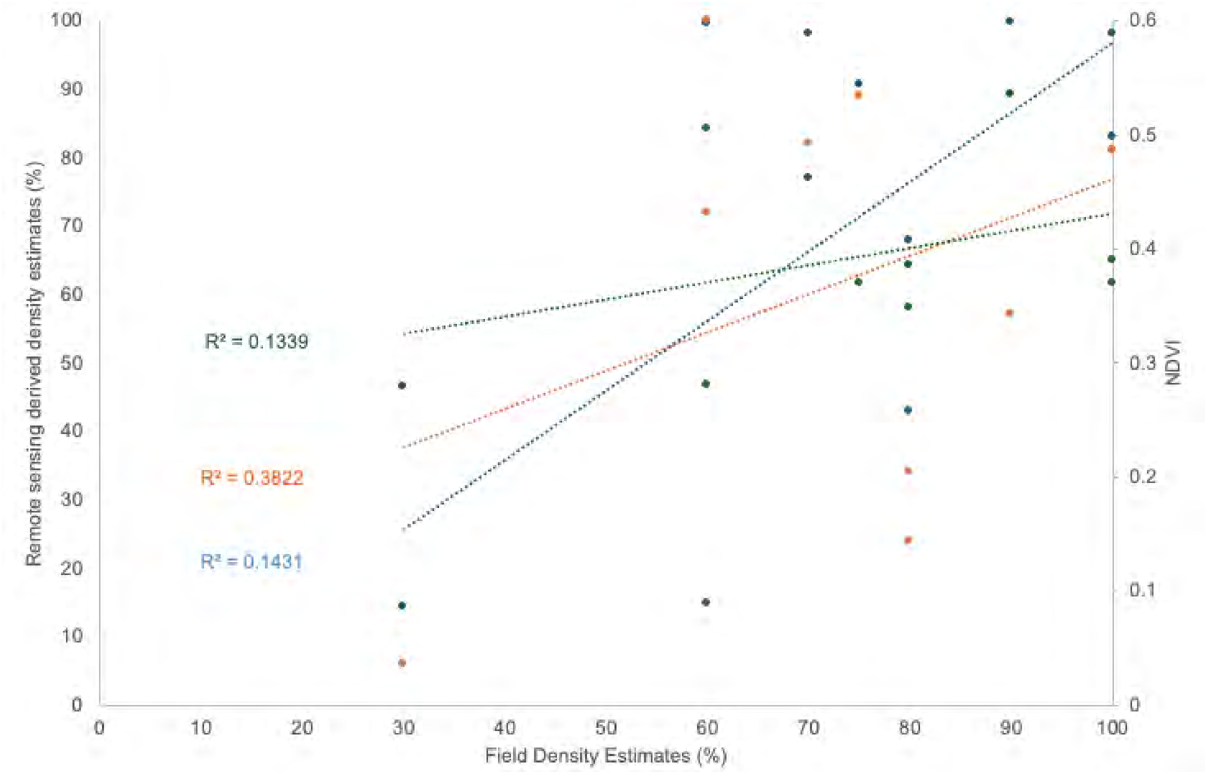


Figure 33. *The correlation between the field and remote sensing estimates of vegetation density (percentage cover) for the four study catchments, South Africa. Blue = Random Forest approach, orange = 100 m grid cell approach, green = NDVI approach.*

5.3. Woody invasive alien plant age

The MODIS burned area dataset has many gaps in the study catchments, and this limits the utility of this dataset for the purpose of mapping invasive alien stand age (**Figure 34**). Spatial results seem to align with in-field knowledge of stand age, with the plantations of Sabie-Crocodile Catchment estimated at around 14-15 years old with some variation, while the uMzimvubu invasions seem to only be several years old (**Table 27**). This could also to some extent link to the natural fire regimes in the area (return interval of around 3-4 years in the Drakensberg foothill grasslands, and longer in the bushveld).

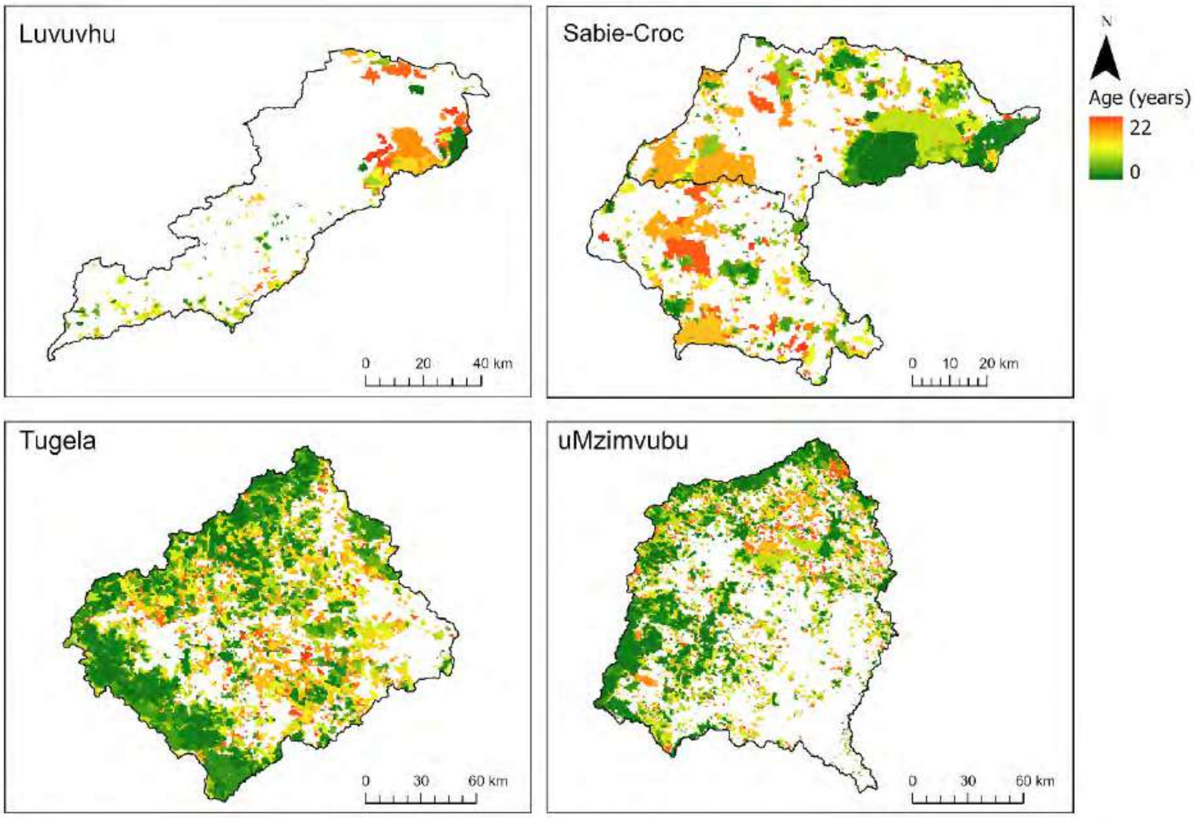


Figure 34. *An estimate of vegetation age for each of the four study catchments for the last 22 years, based on time since fire derived from MODIS burned area data.*

Table 27. The mean ± standard deviation of the age of woody invasive alien plants in the four different catchments and overall.

	Luvuvhu	Sabie-Croc	Tugela	uMzimvubu	Mean
Gum	10 ± 4.7	14 ± 4.8	8 ± 6.9	4 ± 6.3	**9 ± 5.7**
Pine	11 ± 1.6	15 ± 3.5	11 ± 6.2	3 ± 5.8	**10 ± 4.3**
Wattle			6 ± 5.7		**6 ± 5.7**
Black/Green Wattle				3 ± 5.3	**3 ± 5.3**
Silver Wattle				3 ± 5.8	**3 ± 5.8**
Poplar			9 ± 7.2	4 ± 6.2	**6 ± 6.7**
Other	11 ± 6	12 ± 5.1	6 ± 5.6	2 ± 4.6	**8 ± 5.3**
Bugweed	12 ± 3.2	13 ± 5.7			**12 ± 4.5**
Lantana	12 ± 4.2	11 ± 5.9			**11 ± 5.1**
Yellow Bells		10 ± 6.2			**10 ± 6.2**
Mean	**5.6 ± 1.97**	**7.5 ± 3.12**	**4 ± 3.16**	**1.9 ± 3.4**	**7.8 ± 5.46**

Field-collected height data were converted to rough age estimates based on expert forestry opinion for a few examples to validate the vegetation age approach applied in this study. This demonstrates that upon closer scrutiny the field estimated stand age does not relate well to the age estimated from the MODIS burned area data (**Table 28**), and therefore this method is not recommended. Given that the age according to this remote sensing-derived method is often greater than the field estimated age, it would suggest that some fires are not being recorded. This could be due to weather conditions, e.g. cloud cover in the rainy season. However, this seems unlikely as these ecosystems do not typically burn in the rainy season (in this case, the summer), but in the dry winter. Another reason could be that smaller fires are not detected, but this again seems unlikely as often in these systems the fires can be extensive. Therefore, the conclusion is that at this stage the MODIS burned area data are insufficiently accurate enough to derive vegetation age at this scale. Interestingly however, the correlation between field and remote sensing-derived vegetation age estimates is reasonable (R^2=0.6, **Figure 35**), however the age estimates are out by around an order of magnitude.

Table 28. *The results of the remote sensing invasive alien plant age method, relative to field notes, for a few examples from the study catchments, South Africa. Photos are provided in* ***Plate 10****.*

Catchment	Class	Coordinates	Details	Field (years)	Remote sensing (years)
uMzimvubu	Silver Wattle	28.85101667; -30.2429447	Small trees just beyond seedling stage (1 m).	1	9.4
	Gum	28.2673426; -31.0268106	Mature plantation (15 m in height). Trees are near the harvesting stage.	8-10	20.5
Sabie-Crocodile	Pine	30.768005; -25.301667	Young pine plantation block, they are about 2-3 m in height.	3-4	15.5
Tugela	Wattle	29.5274140; -29.0815318	Black Wattle stand with most trees between 2 -3 m in height. Age estimated at around 2 years.	2	12.4
	Pine	29.439252; -28.9884846	Pine plantation block with trees 3 – 4 m in height.	3-4	12.5
Luvuvhu	Gum	29.9233729; -23.0188583	Gum plantation block with young trees of about 2.5 – 3 m in height. The canopy closure and lack of pruning suggests that these trees are around 2-3 years old.	2	2.4

A Silver Wattle invasion of about 1-1.5 m in height in the grassland of the uMzimvubu Catchment.

A mature gum plantation about 15 m in height, in the uMzimvubu Catchment. Trees seems to be near harvesting stage.

A young pine block plantation in the Tugela Catchment, trees are about 3-4 m in height.

An infestation of wattle stand with trees between 2-3 m in height..

A young pine plantation in the Sabie-Crocodile, the trees are between 2-3 m in height.

A young gum plantation block in the Luvhuvu Catchment, The trees are about 2.5-3 m in height. The canopy closure and lack of pruning suggest the trees are approximately 2-3 years old.

Plate 10. *Photographic evidence for the examples described in* ***Table 28****.*

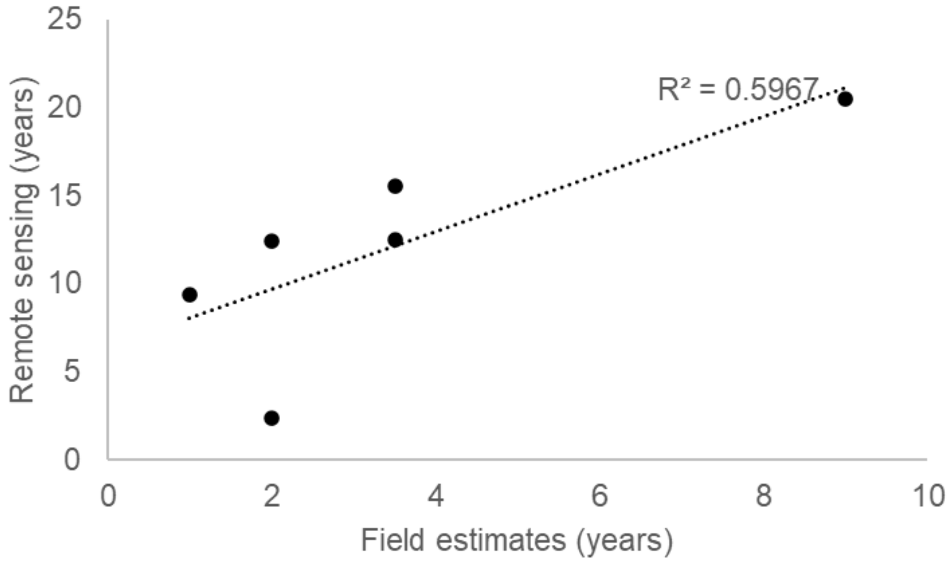


Figure 35. *The correlation between the field and remote sensing estimates of vegetation age (years) for the four study catchments, South Africa.*

5.4. Woody invasive alien plant water-use

At the catchment level, total evapotranspiration was similar among catchments, and relatively consistent over the last five years, justifying the use of the five-year mean evapotranspiration results, rather than the last year (**Figure 36**). Using five years is more robust, as it considers inter-annual climatic variation, and minimizes the risk of using an outlier year in terms of climate by chance. The risk of this approach is that over the last five years, there may have been some changes on the landscape, e.g. fires, clear-felling of plantations etc. However this is the trade-off that has to be considered.

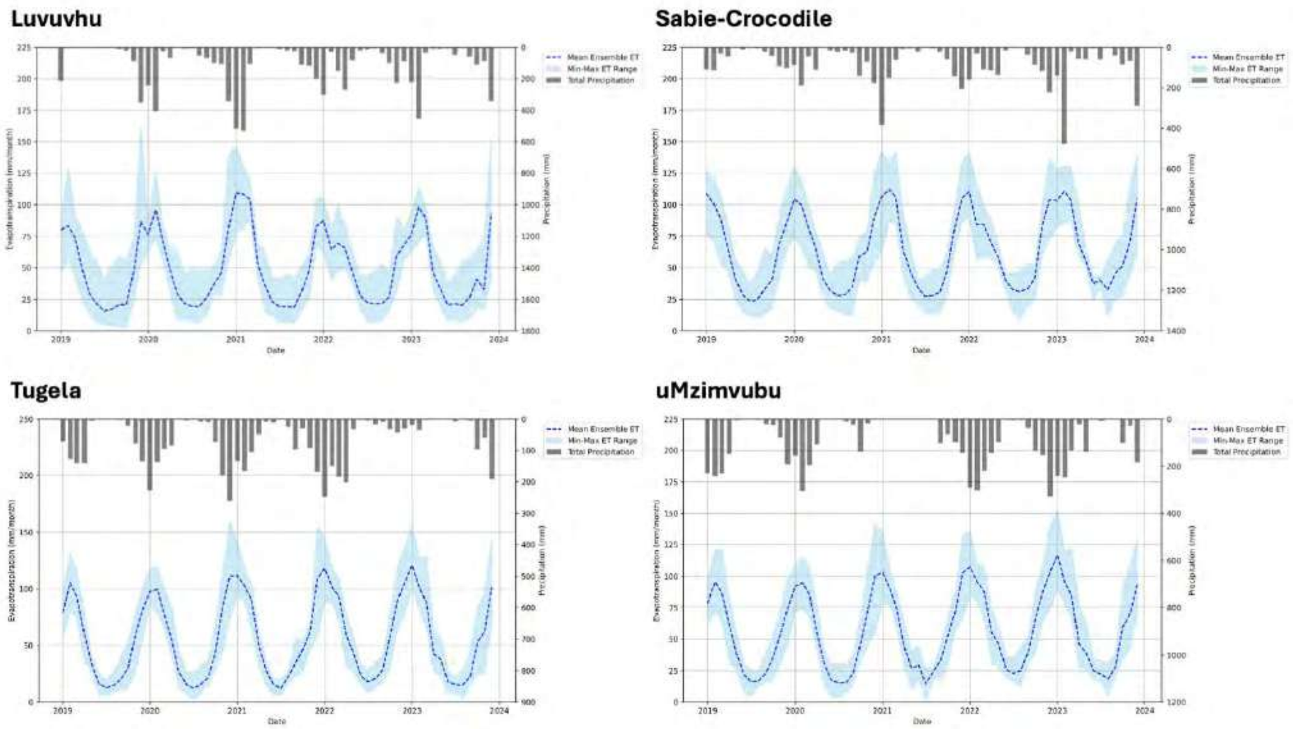


Figure 36. *The mean and range (min to max) of catchment-level evapotranspiration on a monthly timestep between 2019 and 2024 based on the developed remote sensing ensemble. The precipitation data are from individual ARC weather stations within each catchment, and so serve as an indicator of rainfall for the catchment, but should not be considered representative of the entire catchment. Rainfall station numbers are: Thouyandou 30753, Hazyview 30859, Bergville 30969 and Underberg 30993 for each of the four study catchments respectively.*

The highest five-year mean annual evapotranspiration is recorded in the uMzimvubu Catchment near the confluence of the river with the ocean (**Figure 37**). However very high evapotranspiration was also recorded in the Luvuvhu Catchment on the slopes of the Soutpansberg Mountains, as well as in the Sabie-Crocodile Catchments, just below the escarpment. Both areas have large tracts of forestry plantations. The Tugela Catchment has the lowest maximum evapotranspiration of the four study catchments, and these do not align with the Drakensberg Mountain Range or escarpment, but rather appear to be riparian zones, or forestry plantation blocks. The lowest minimum evapotranspiration is recorded in the Luvuvhu Catchment, in the northeast.

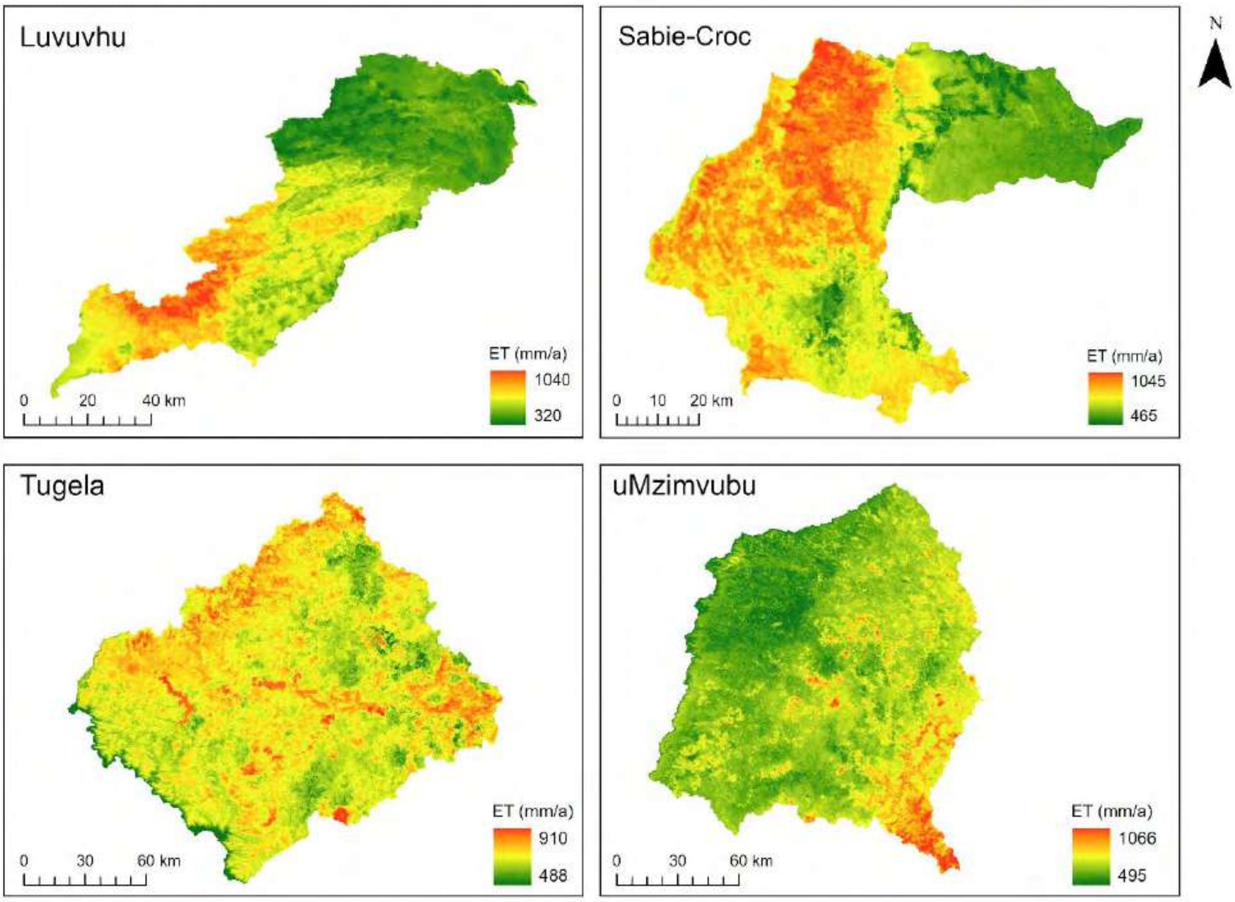


Figure 37. *Mean annual evapotranspiration (ET) over a 5-year period (2019-2023) for the four study catchments, South Africa.*

The ratio of evapotranspiration to rainfall within the surface water strategic water source area portions of the catchments were all over 80%, regardless of the magnitude of precipitation (**Table 29**).

Table 29. *Hydrological and other parameters for each of the four study catchments, and their surface water strategic water source area (SWSA) portions. MAP = mean annual precipitation.*

Catchment	**Luvuvuhu**	**Sabie-Croc**	**Tugela**	**uMzimvubu**
Catchment MAP (mm/a)	596	926	888	824
Catchment mean annual ET (mm/a)	587	768	673	675
Catchment ET/MAP Ratio (%)	98	83	76	82
SWSA MAP (mm/a)	939	965	844	831
SWSA Mean annual ET (mm/a)	842	842	677	662
SWSA ET/MAP Ratio (%)	87	87	80	80
Catchment area (km^2)	6888	5410	7622	19 844
SWSA area (km^2)	1635 (24%)	3130 (58%)	3883 (51%)	11 284 (57%)
Area plantations in catchment (km^2)	231 (3%)	1666 (31%)	77 (1%)	642 (3%)
Area plantations in SWSA (km^2)	217 (13%)	1660 (53%)	73 (2%)	583 (5%)
SWSA Name(s)	Soutpansberg	Mpumalanga Drakensberg	Northern Drakensberg	Eastern Cape Drakensberg, Southern Drakensberg

5.4.1. Luvuvhu Catchment

In general the alien category has higher evapotranspiration than all indigenous classes, with the exception of indigenous forest (**Table 30**, **Figure 38**). Only the class “alien other”, which includes herbaceous taxa, has a lower evapotranspiration relative to the indigenous classes. Mopane-dominated bush has the lowest evapotranspiration. In this catchment, pine has the highest evapotranspiration of all the woody invasive alien trees, higher even than gums. Agricultural evapotranspiration is comparable to that of woody invasive alien plants, except for dryland (rainfed) agriculture. Irrigated agriculture also has a lower evapotranspiration relative to other agricultural land-uses, such as orchards and nuts etc. The reason for this is the specific characteristics of irrigated agriculture in the Luvuvhu. We included irrigated maize and leafy crops (e.g. spinach, kale, cabbage). These were mostly small-scale/subsistence crops, and not irrigated with pivots, but with sprinklers or drop irrigation. Orchards, nuts, bananas and tea were all large-scale commercial agriculture, with much more sophisticated irrigation schemes. Because the subsistence irrigated agriculture was so small scale, it was often situated within a dryland agricultural context, e.g. rainfed crops, with small portions of irrigated crops. This could have resulted in slightly lower recorded evapotranspiration values for this irrigated agriculture, due to scale. Therefore, the results should be interpreted with this in mind. Large scale, commercial irrigated agriculture is not likely to have similar evapotranspiration results.

Table 30. *Statistics for evapotranspiration (ET) for the last five years (2019-2023) for each land-use/land-cover class for the Luvuvhu Catchment, South Africa (mm/a).*

Category	Class	Minimum	Maximum	Range	Mean	St Dev
Alien	Gum	413.9	1018.0	604.0	833.9	92.9
	Pine	556.2	1028.2	472.0	880.5	58.8
	Lantana	510.8	1004.5	493.7	735.1	71.9
	Bugweed	507.7	1015.6	507.9	767.0	83.0
	Other	420.1	1003.2	583.1	659.5	96.3
Agriculture	Dryland	325.5	975.4	649.9	501.8	89.5
	Irrigated	338.0	971.3	633.3	566.8	94.1
	Bananas	558.1	985.5	427.4	770.4	79.2
	Nuts	406.6	1036.4	629.8	773.0	91.7
	Orchards	459.2	1029.7	570.4	740.4	83.2
	Tea	599.7	1016.1	416.4	877.5	61.8
Indigenous	Bush (Mopane)	319.3	924.0	604.8	530.2	72.8
	Bush (Other)	414.9	1037.7	622.9	693.2	76.2
	Forest	439.2	1037.0	597.8	837.4	83.0
	Wetland	384.7	1001.2	616.5	667.7	82.5
Other	Bare Ground	318.7	942.5	623.8	472.1	94.8
	Urban	338.6	886.1	547.5	552.1	78.9
	Water	347.0	993.4	646.4	657.5	107.9

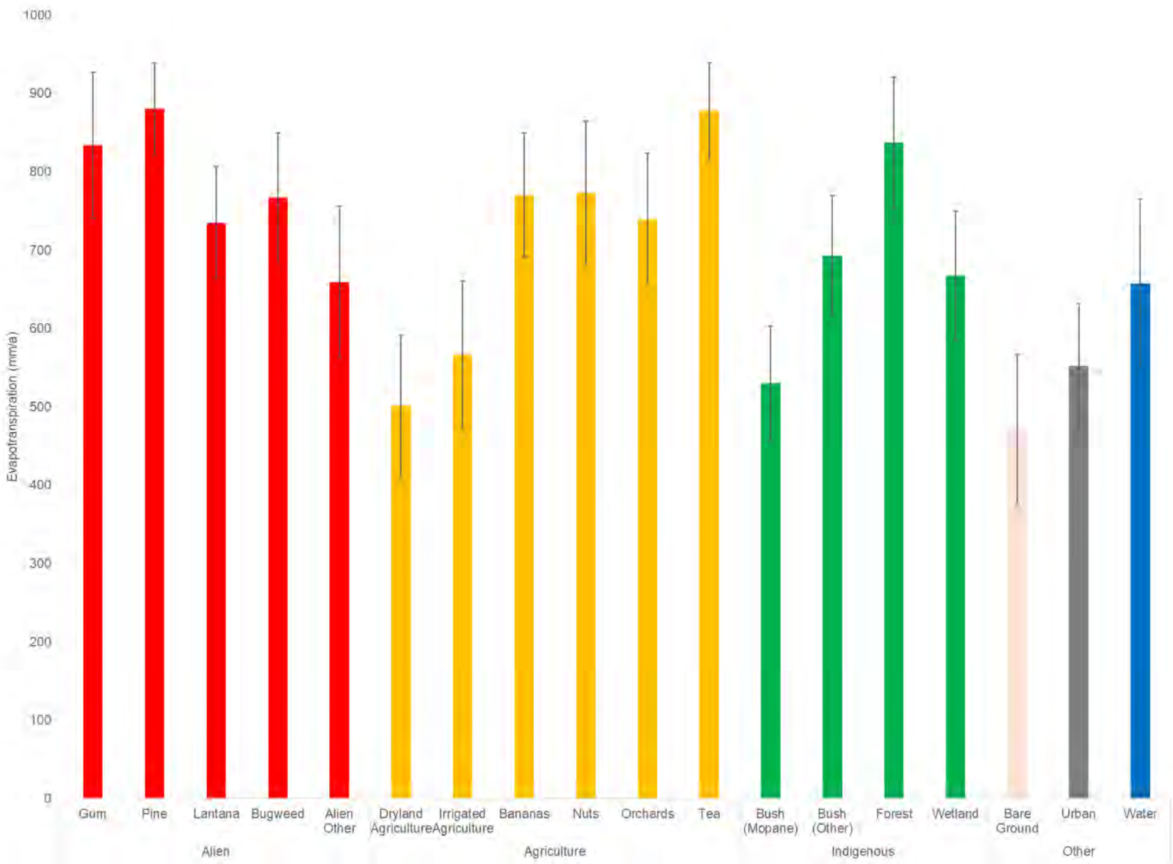


Figure 38. *Mean (±standard deviation) evapotranspiration (mm/a) for the last five years (2019-2023) for each land-use/land-cover (LULC) class for the Luvuvhu Catchment, South Africa.*

Relative water-use

It is important to consider that if the purpose of invasive alien tree clearing is to restore indigenous classes, then the most appropriate class should be considered, relative to a reference ecosystem (i.e. whether the comparison is to indigenous forest or bush is pre-determined by ecological factors). If the decision to be made is to consider a shift from a plantation to a different crop, for example banana or nuts, then there is more freedom of selection, although there will be soil and microclimate factors to consider as well (which is out of the scope of this research). Therefore the following tables only show the relative water gains associated with a land-use change, with no other factors considered and should not be applied without ecological and agricultural expertise as applicable.

The largest gains in water are from a transition from invasive alien trees such as gum, pine, but also from Bugweed to indigenous vegetation classes and dryland (rainfed) agriculture (**Figure 39**, **Figure 40**). Differences between invasive alien pines and gum, and dryland and irrigated agriculture, and Mopane-dominated indigenous bush were around 300 mm/a. The difference between pines and gums and tea plantations and indigenous forest were negligible, although pine did appear to use slightly more water relative to indigenous forest, but with large variation.

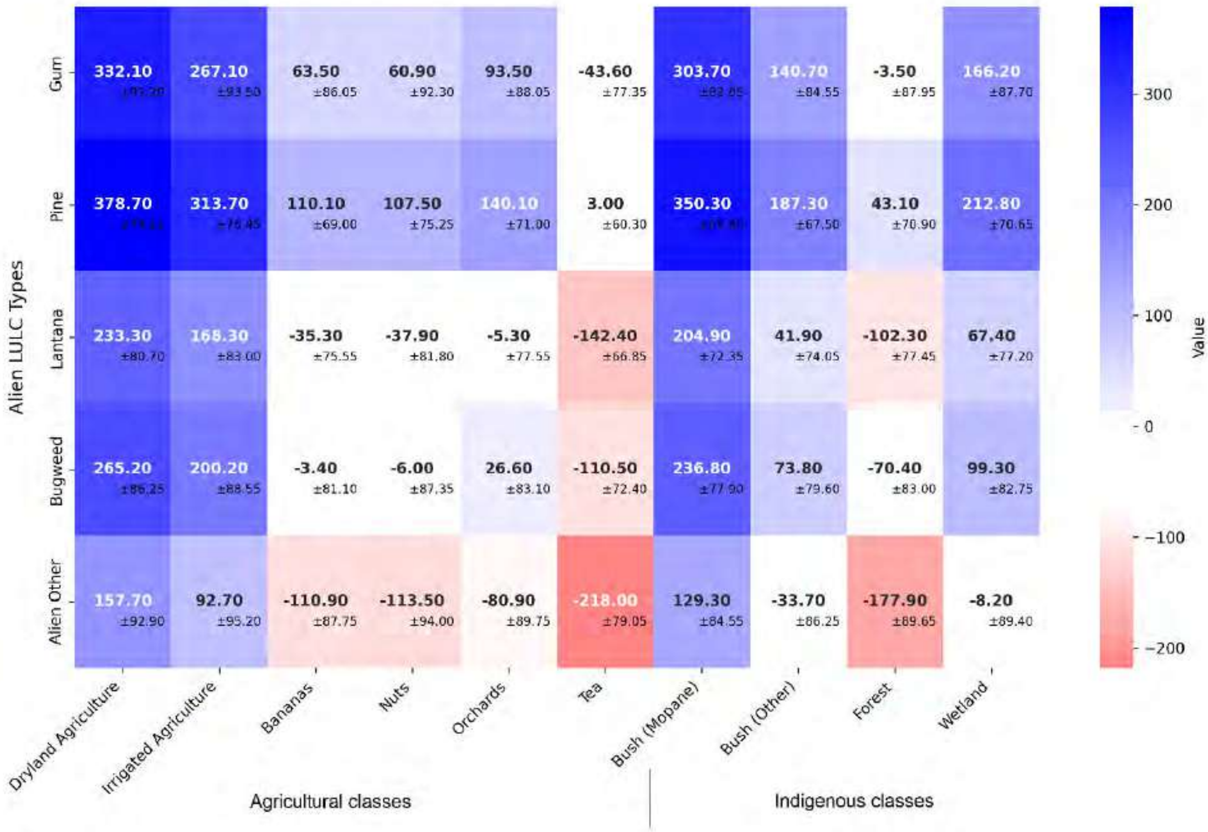
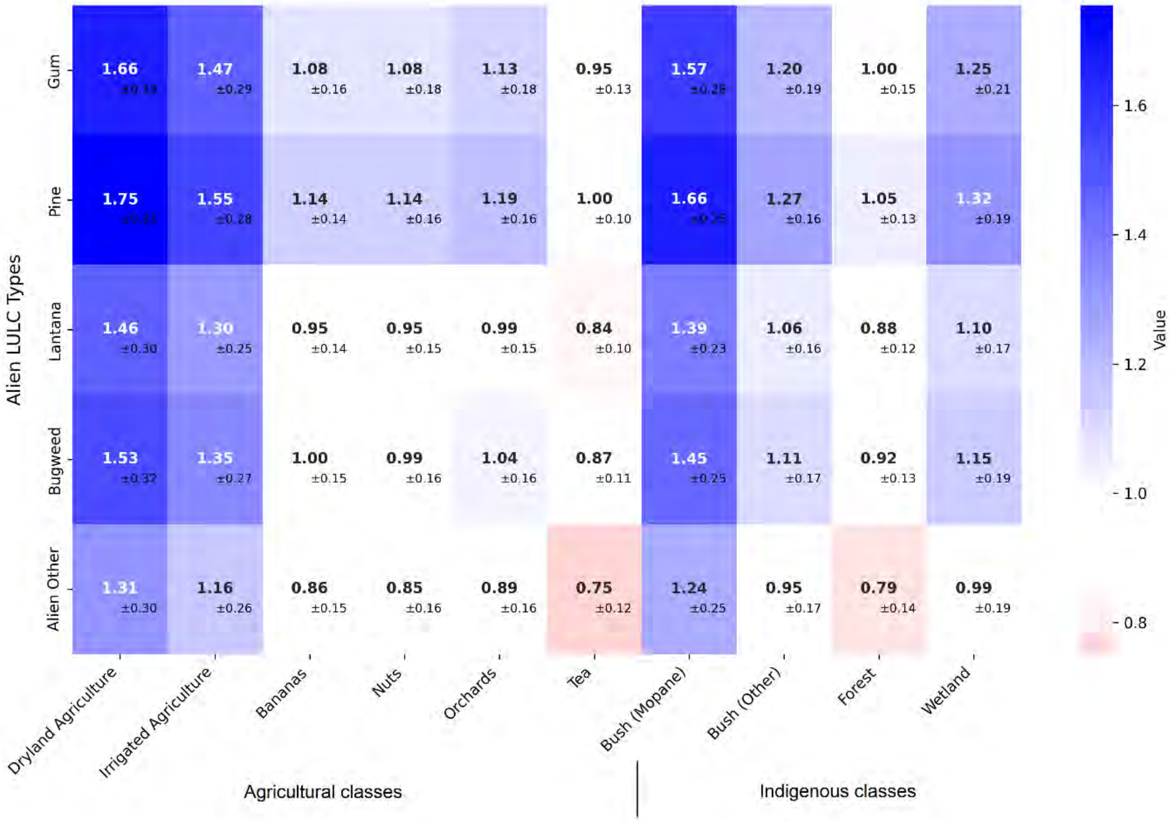


Figure 39. *The relative water-use (mm/a) for some key land-use/land-cover classes for the Luvuvhu Catchment, South Africa. Water gains are in blue, losses in red, and no change in white.*



Alien LULC Types	Dryland Agriculture	Irrigated Agriculture	Bananas	Nuts	Orchards	Tea	Bush (Mopane)	Bush (Other)	Forest	Wetland
Gum	1.66	1.47 ±0.29	1.08 ±0.16	1.08 ±0.18	1.13 ±0.18	0.95 ±0.13	1.57	1.20 ±0.19	1.00 ±0.15	1.25 ±0.21
Pine	1.75	1.55 ±0.28	1.14 ±0.14	1.14 ±0.16	1.19 ±0.16	1.00 ±0.10	1.66	1.27 ±0.16	1.05 ±0.13	1.32 ±0.19
Lantana	1.46 ±0.30	1.30 ±0.25	0.95 ±0.14	0.95 ±0.15	0.99 ±0.15	0.84 ±0.10	1.39 ±0.23	1.06 ±0.16	0.88 ±0.12	1.10 ±0.17
Bugweed	1.53 ±0.32	1.35 ±0.27	1.00 ±0.15	0.99 ±0.16	1.04 ±0.16	0.87 ±0.11	1.45 ±0.25	1.11 ±0.17	0.92 ±0.13	1.15 ±0.19
Alien Other	1.31 ±0.30	1.16 ±0.26	0.86 ±0.15	0.85 ±0.16	0.89 ±0.16	0.75 ±0.12	1.24 ±0.25	0.95 ±0.17	0.79 ±0.14	0.99 ±0.19

Figure 40. *The water-use factor with which to multiply evapotranspiration to understand potential water-related impacts of land-use or land-cover change for the Luvuvhu Catchment, South Africa. Water gains are in blue, losses in red, and no change in white.*

Evapotranspiration inside and outside of strategic water source areas

In the Luvuvhu Catchment there is hardly any difference in water-use factor (i.e. the ratio among different land-use/land-cover classes) inside and outside the surface water strategic water source areas for most classes (**Figure 41**). This is an interesting finding, as it suggests that the relative water-use of different classes remains the same, and therefore the gains of clearing of invasive alien trees and subsequent restoration would be the same within and outside of the strategic water source areas, relatively speaking. It should be considered however that most of the invasions (in terms of area invaded) are within these strategic water source areas. However, there are some notable exceptions: changes from woody invasive alien plants to dryland and irrigated agriculture, as well as bush (Mopane) would yield greater gains in the catchment compared to the surface water strategic water source area. This result may be because most of these non-alien classes are found outside the surface water strategic water source area, with a very small sample size within, leading to erroneous results.

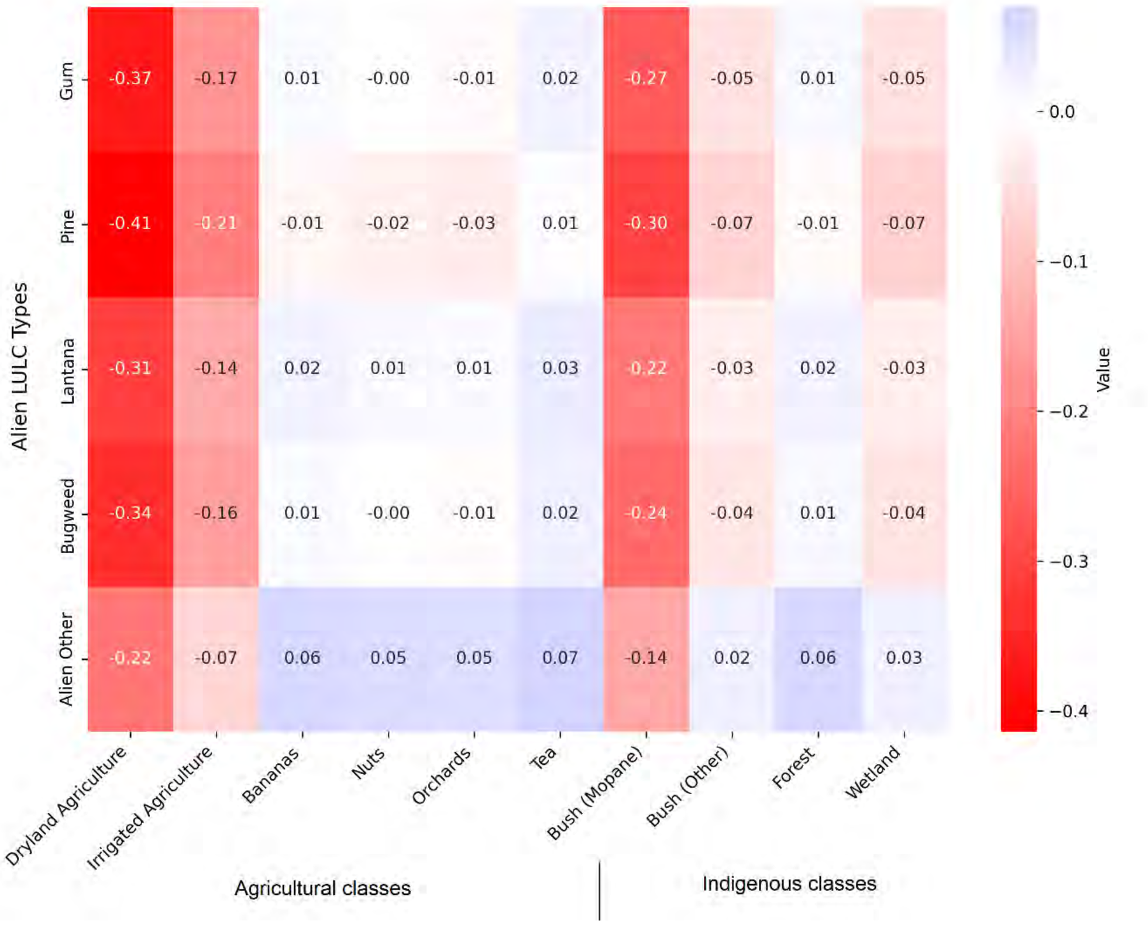


Figure 41. *A comparison of the difference in the water-use factor between the surface water strategic water source area portion of the Luvuvhu Catchment South Africa, and the entire catchment. Blue indicates higher water-use in the strategic water source area, red indicates higher water-use in the catchment, and white shows no difference.*

Potential water savings with invasive alien tree clearing
Relative and linear (mm/a) water-use impacts (i.e. differences in evapotranspiration) are interesting theoretically. However in practice, if there are only small woody alien plant invasions, then the water impact will be small. Likewise, if there are large areas of invasion, the potential water impacts of clearing will be larger. Therefore it is important to understand the area of invasion, and calculate the potential volumes of water that may be released if these invasions are cleared, to quantify actual water impact.

The largest gains in volume in the Luvuvhu are a change from pines to indigenous bush, and from gum to indigenous bush, but specifically Mopane-dominated bush (**Table 31**). A change to indigenous forest would not lead to water gains, however there are many other benefits of restoration to indigenous forest besides water, and these are out of the scope of this research but should be kept in mind when making decisions about land-use change or restoration.

Table 31. *The potential volume of water that could be generated from clearing woody invasive alien plants within the Luvuvhu Catchment, South Africa (in million m^3). These values represent only alien tree invasions, and not plantations. Blue indicates gains, and red losses in volume. Conversion: 1 million m^3 is equivalent to 400 Olympic-sized swimming pools.*

	Gum	**Pine**	**Lantana**	**Bugweed**	**Alien Other**
Bush (Mopane)	6.0	3.9	7.3	4.6	20.1
Bush (Other)	2.8	2.1	1.5	1.4	-5.2
Forest	-0.1	0.5	-3.7	-1.4	-27.6
Wetland	3.3	2.3	2.4	1.9	-1.3
Dryland Agriculture	6.5	4.2	8.3	5.1	24.5
Irrigated Agriculture	5.2	3.5	6.0	3.9	14.4
Bananas	1.2	1.2	-1.3	-0.1	-17.2
Nuts	1.2	1.2	-1.4	-0.1	-17.6
Orchards	1.8	1.5	-0.2	0.5	-12.6
Tea	-0.9	0.0	-5.1	-2.1	-33.8

5.4.2. Sabie-Crocodile Catchment

In general for the Sabie-Crocodile Catchment the alien category has higher evapotranspiration than all indigenous classes, with the exception of indigenous forest, but the difference is less pronounced relative to the Luvuvhu Catchment (**Table 32**, **Figure 42**). In this catchment, gum has the highest evapotranspiration of all the woody invasive alien trees, higher even than pines, and higher than indigenous forest. Pine and indigenous forest have comparative evapotranspiration. Agricultural evapotranspiration is comparable to that of woody invasive alien plants.

Table 32. *Statistics for evapotranspiration (ET) for the last five years (2019-2023) for each land-use/land-cover class for the Sabie-Crocodile Catchment, South Africa (mm/a).*

Category	Class	Minimum	Maximum	Range	Mean	St Dev
Alien	Bugweed	485.5	1017.1	531.6	813.1	79.1
	Gum	530.0	1042.1	512.1	903.7	61.3
	Lantana	526.6	1011.7	485.1	782.8	85.4
	Other	494.8	1034.0	539.1	810.5	99.2
	Pine	611.1	1038.5	427.3	878.6	55.0
	Yellow Bells	496.8	988.2	491.4	760.5	84.9
Agriculture	Bananas	655.6	994.5	338.8	832.9	63.0
	Grassland	475.1	1018.5	543.4	671.7	89.0
	Macadamias	499.5	1045.0	545.6	839.0	95.7
	Orchards	464.6	1041.4	576.9	804.8	93.6
Indigenous	Bush	474.6	1032.8	558.2	742.2	89.7
	Forest	564.3	1043.7	479.3	880.1	70.6
	Wetland	474.7	1044.3	569.6	751.6	98.6
Other	Bare Ground	477.1	1016.5	539.4	670.9	120.0
	Burnt	541.5	990.0	448.5	764.6	77.0
	Urban	468.0	997.7	529.7	655.8	93.4
	Water	506.9	996.8	489.9	823.4	71.6

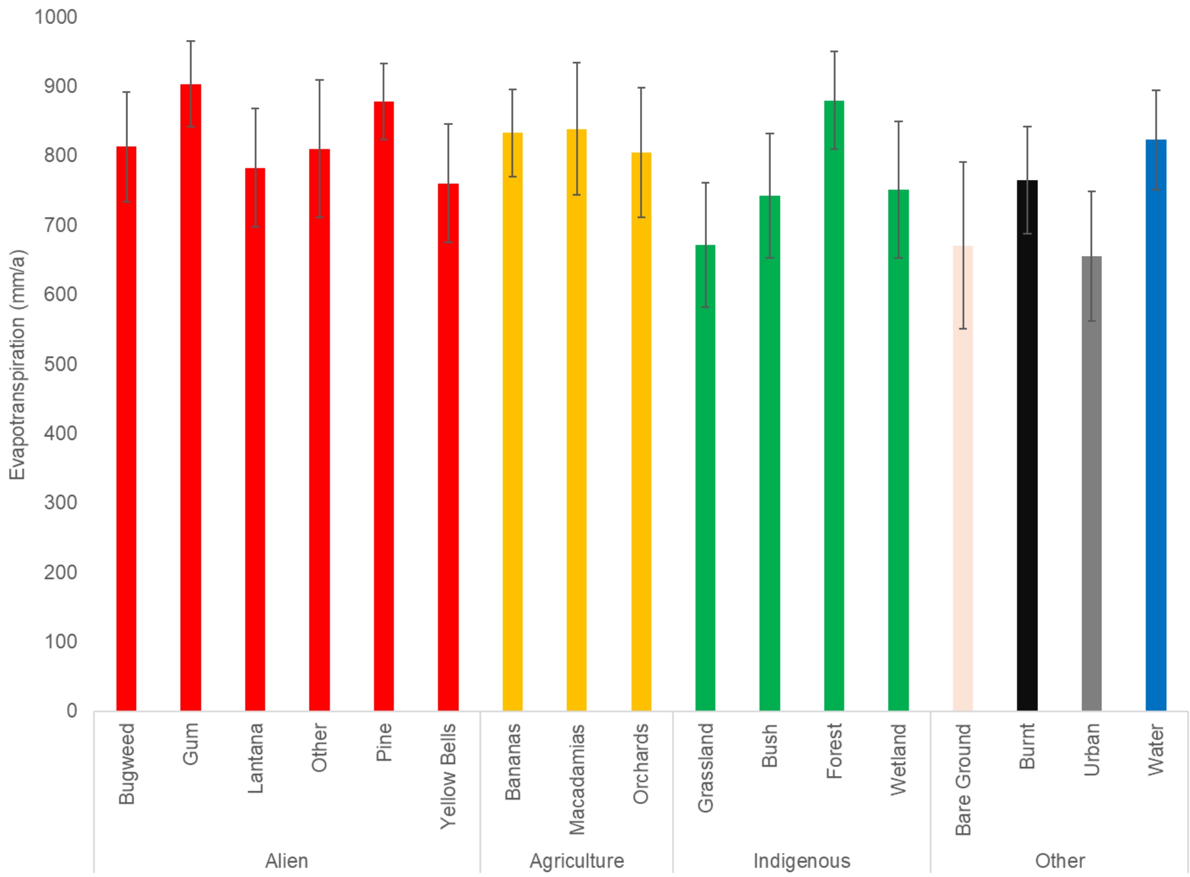


Figure 42. *Mean (±standard deviation) evapotranspiration (mm/a) for the last five years (2019-2023) for each land-use/land-cover (LULC) class for the Sabie-Crocodile Catchment, South Africa.*

Relative water-use

It is important to consider that if the purpose of invasive alien tree clearing is to restore indigenous classes, then the most appropriate class should be considered, relative to a reference ecosystem (i.e. whether the comparison is to indigenous forest or bush is pre-determined by ecological factors). If the decision to be made is to consider a shift from a plantation to a different crop, for example banana or nuts, then there is more freedom of selection, although there will be soil and microclimate factors to consider as well (which is out of the scope of this research). Therefore the following tables only show the relative water gains associated with a land-use change, with no other factors considered and should not be applied without ecological and agricultural expertise as applicable.

In this catchment, the largest gains in water are from a transition from invasive alien trees such as gum and pine, to indigenous vegetation classes such as grasslands, bush and wetlands (**Figure 43**, **Figure 44**). In the Sabie-Crocodile Catchment, the water-use of gum and pine is very similar.

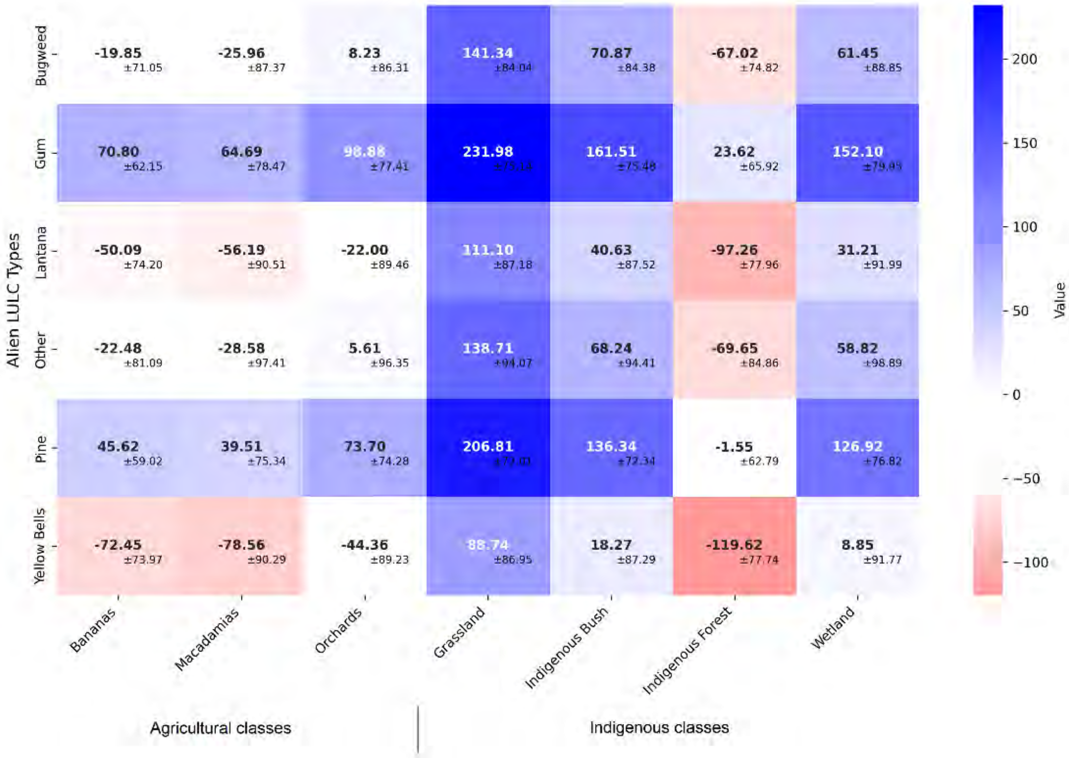


Figure 43. *The relative water-use (mm/a) for some key land-use/land-cover classes in the Sabie-Crocodile Catchment, South Africa. Water gains are in blue, losses in red, and no change in white.*

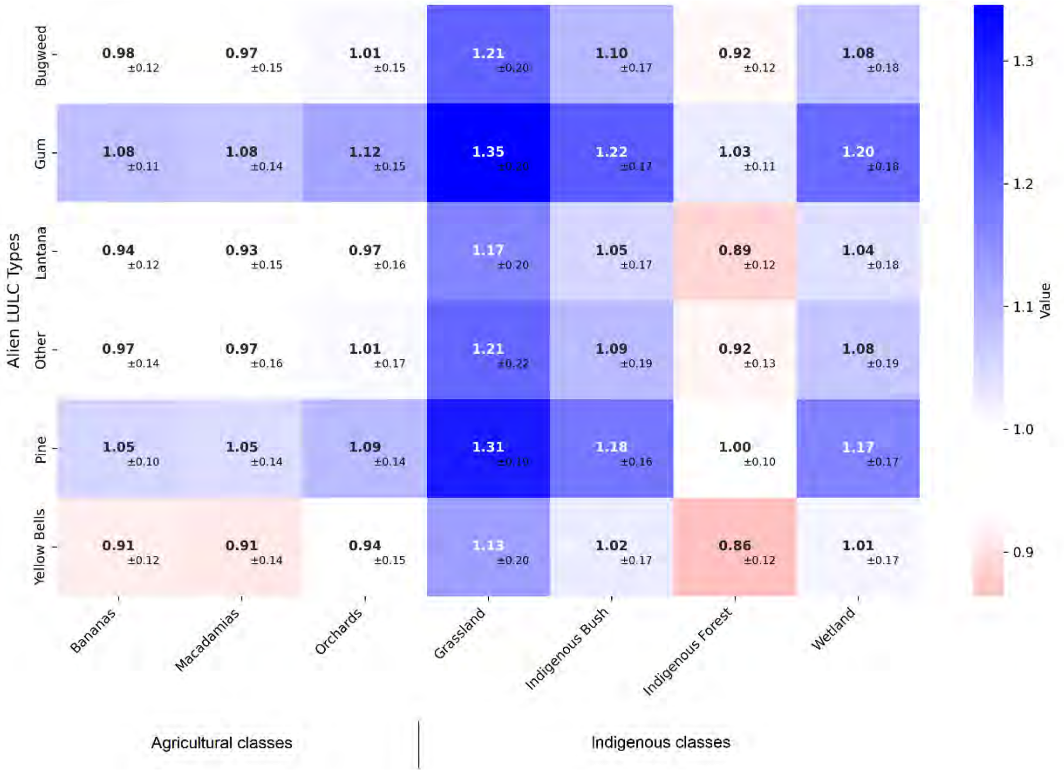


Figure 44. *The water-use factor with which to multiply evapotranspiration to understand potential water-related impacts of land-use or land-cover change for the Sabie-Crocodile Catchment, South Africa. Water gains are in blue, losses in red, and no change in white.*

Evapotranspiration inside and outside of strategic water source areas
In the Sabie-Crocodile Catchment there is hardly any difference in water-use factor (i.e. the ratio among different land-use/land-cover classes) inside and outside the surface water strategic water source areas (**Figure 45**). However there is one exception: a shift from almost all alien classes to grassland always yields a gain of water (**Figure 45**). Besides grasslands, these findings suggest that the relative water-use of different classes remains similar, and therefore the gains of clearing of invasive alien trees and subsequent restoration would be the same within and outside of the strategic water source areas, relatively speaking. It should be borne in mind however that most of the invasions (in terms of area invaded) are within these strategic water source areas.

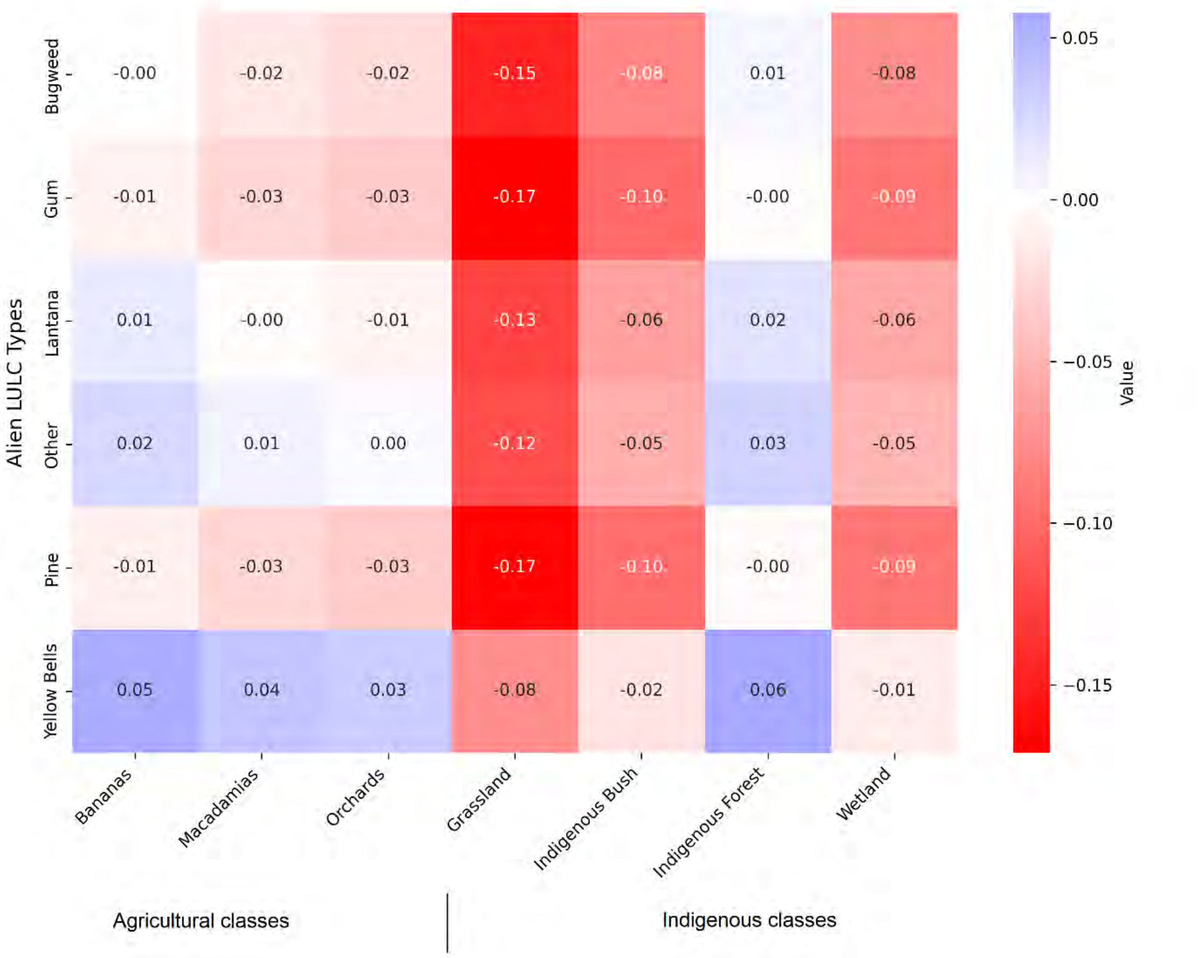


__Figure 45.__ A comparison of the difference in the water-use factor between the surface water strategic water source area portion of the Sabie-Crocodile Catchment, and the entire catchment. Blue indicates higher water-use in the strategic water source area, red indicates higher water-use in the catchment, and white shows no difference.

Potential water savings with invasive alien tree clearing
Relative and linear (mm/a) water-use impacts (i.e. differences in evapotranspiration) are interesting theoretically. However in practice, if there are only small woody alien plant invasions, then the water impact will be small. Likewise, if there are large areas of invasion, the potential water impacts of clearing will be larger. Therefore it is important to understand the area of invasion, and calculate the potential volumes of water that may be released if these invasions are cleared, to quantify actual water impact.

A shift from pine and gums to any indigenous classes, or agricultural classes in the Sabie-Crocodile Catchment produces a gain ranging from 23-123 million m^3. This is besides indigenous forest which uses the same amount of water on average as pine and gum plantations and invasions (**Table 33**).

Table 33. *The potential volume of water that could be generated from clearing woody invasive alien plants within the Sabie-Crocodile Catchment, South Africa (in million m^3). These values represent only alien tree invasions, and not plantations. Blue indicates gains, and red losses in volume. Conversion: 1 million m³ is equivalent to 400 Olympic-sized swimming pools.*

	Gum	**Pine**	**Bugweed**	**Lantana**	**Yellow Bells**	**Other**
Grassland	7.86	9.41	9.46	3.38	1.75	3.34
Indigenous Bush	5.48	6.20	4.74	1.24	0.36	1.64
Indigenous Forest	0.80	-0.07	-4.48	-2.96	-2.36	-1.68
Wetland	5.16	5.77	4.11	0.95	0.17	1.42
Bananas	2.40	2.08	-1.33	-1.52	-1.43	-0.54
Macadamias	2.19	1.80	-1.74	-1.71	-1.55	-0.69
Orchards	3.35	3.35	0.55	-0.67	-0.87	0.14

5.4.3. Tugela Catchment

In general the alien category has similar evapotranspiration to indigenous forest and bush (Vachellia), however gum plantations consume the most water (**Table 34**, **Figure 46**). Bracken, grasslands and wetlands have a lower evapotranspiration relative to bush and forest. Irrigated agriculture has similar evapotranspiration to woody invasive alien trees, and much higher than rainfed agriculture (dryland).

Table 34. *Statistics for evapotranspiration (ET) for the last five years (2019-2023) for each land-use/land-cover class for the Tugela Catchment, South Africa (mm/a).*

Category	Class	Minimum	Maximum	Range	Mean	St Dev
Alien	Gum	641.4	877.2	235.8	762.1	47.6
	Other	552.5	830.3	277.7	690.0	38.4
	Pine	616.6	856.2	239.6	715.6	37.4
	Poplar	584.3	864.7	280.4	717.1	41.6
	Wattle	605.0	864.1	259.1	725.9	43.7
Agriculture	Dryland Agriculture	529.0	864.9	335.9	662.7	32.4
	Irrigated Agriculture	586.7	874.4	287.7	723.3	40.1
Indigenous	Bracken	544.4	872.0	327.6	672.4	43.2
	Grassland	492.6	856.0	363.4	669.4	40.5
	Bush (Other)	518.9	852.4	333.5	686.1	39.9
	Bush (Vachellia)	540.5	853.0	312.5	715.2	37.8
	Forest	596.0	854.0	258.0	708.7	40.9
	Wetland	504.4	874.2	369.9	684.8	40.9
Other	Bare Ground	505.3	838.1	332.9	650.7	47.4
	Burnt	514.2	817.9	303.7	663.3	44.2
	Urban	502.9	807.3	304.4	628.6	52.9
	Water	504.8	846.6	341.8	730.8	60.1

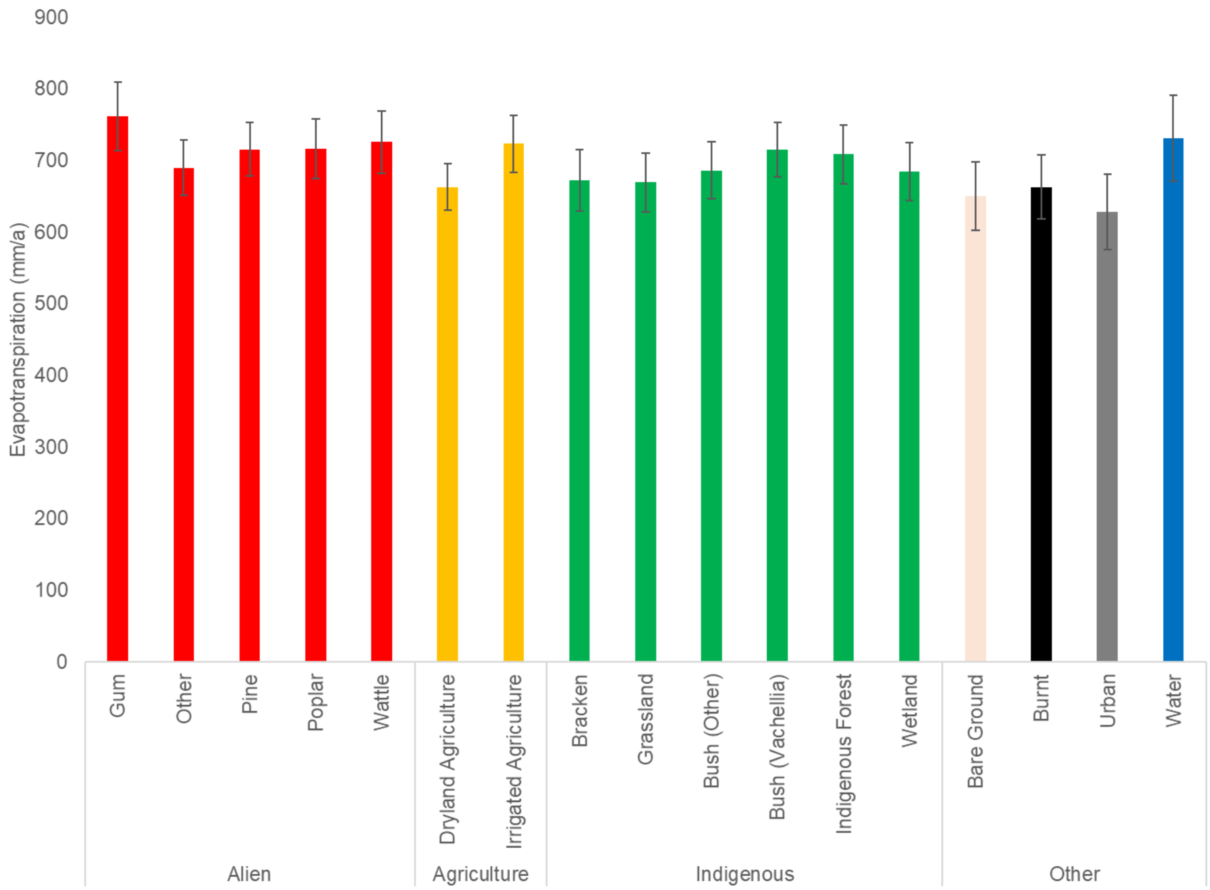


Figure 46. *Mean (±standard deviation) evapotranspiration (mm/a) for the last five years (2019-2023) for each land-use/land-cover (LULC) class for the Tugela Catchment, South Africa.*

Relative water-use

It is important to consider that if the purpose of invasive alien tree clearing is to restore indigenous classes, then the most appropriate class should be considered, relative to a reference ecosystem (i.e. whether the comparison is to indigenous forest or bush is pre-determined by ecological factors). If the decision to be made is to consider a shift from a plantation to a different crop, for example banana or nuts, then there is more freedom of selection, although there will be soil and microclimate factors to consider as well (which is out of the scope of this research). Therefore the following tables only show the relative water gains associated with a land-use change, with no other factors considered and should not be applied without ecological and agricultural expertise as applicable.

The largest gains in water are from a transition from gums to indigenous vegetation classes such as bracken, grassland, bush (other) and wetland as well as dryland (rainfed) agriculture (**Figure 47**, **Figure 48**). Wattle also has a high water-use compared to the others, followed by pine and poplar. Gum uses slightly more water relative to pine in the Tugela Catchment.

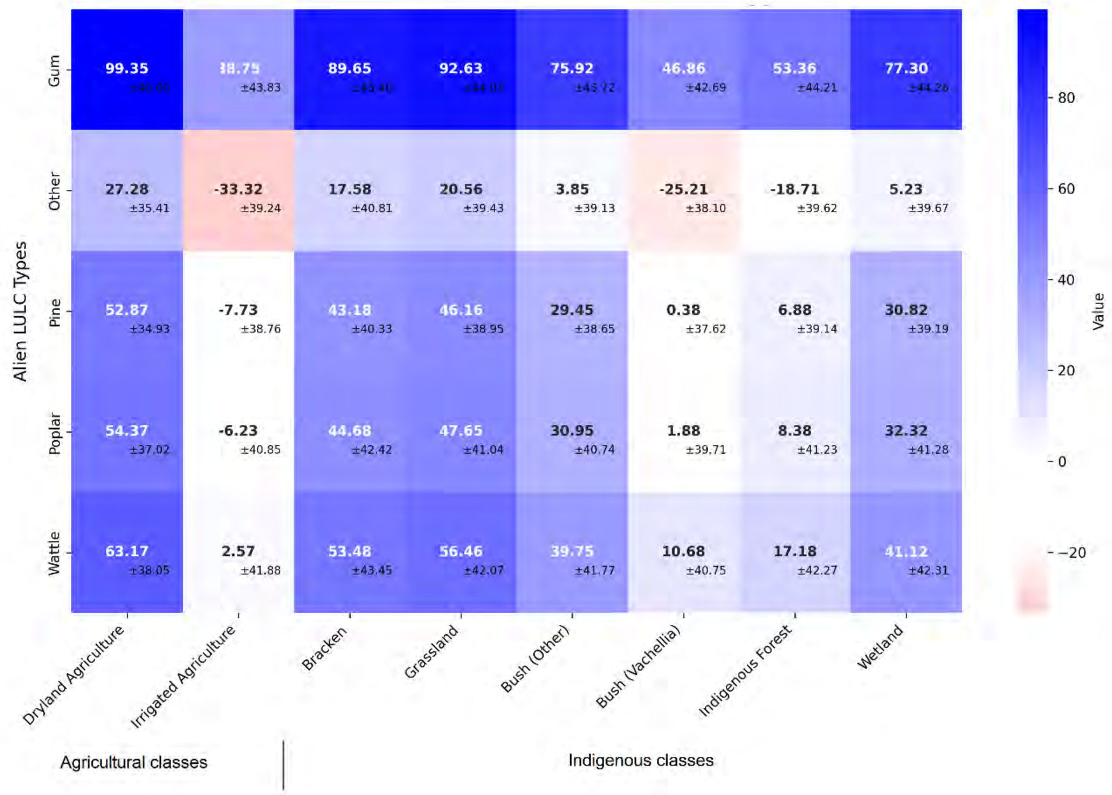


Figure 47. *The relative water-use (mm/a) for some key land-use/land-cover classes in the Tugela Catchment, South Africa. Water gains are in blue, losses in red, and no change in white.*

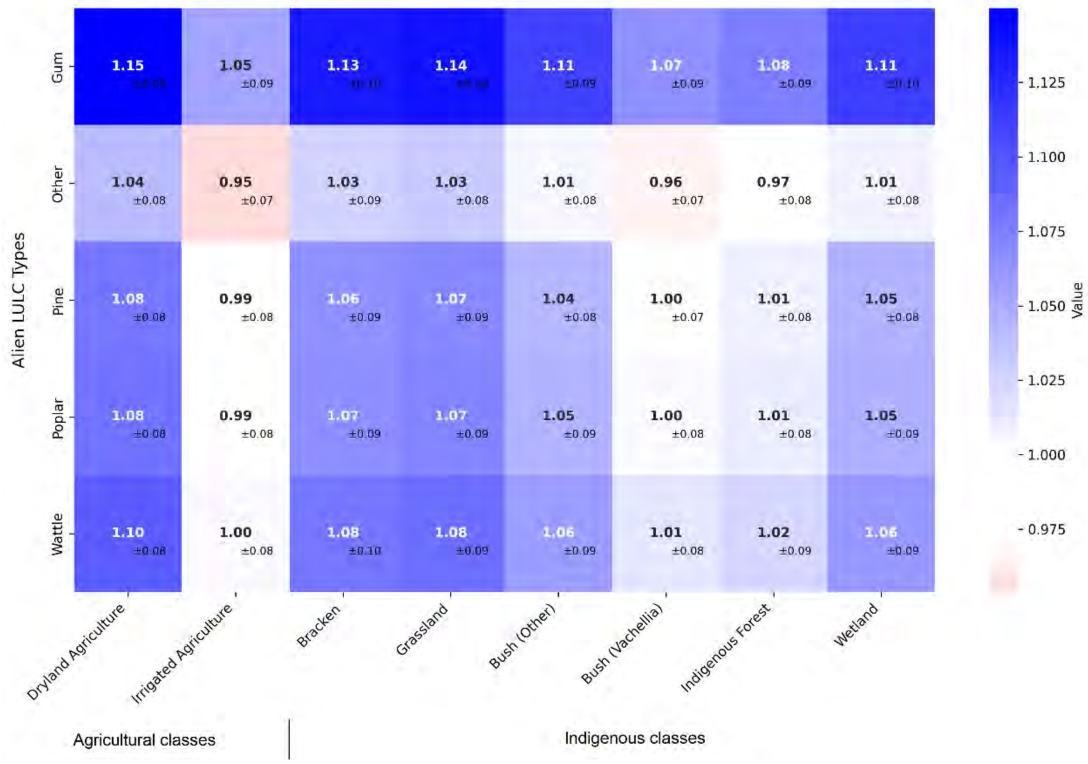


Figure 48. *The water-use factor with which to multiply evapotranspiration to understand potential water-related impacts of land-use or land-cover change in the Tugela Catchment, South Africa. Water gains are in blue, losses in red, and no change in white.*

Evapotranspiration inside and outside of strategic water source areas

In the Tugela Catchment there is hardly any difference in water-use factor (i.e. the ratio among different land-use/land-cover classes) inside and outside the surface water strategic water source areas (**Figure 49**).

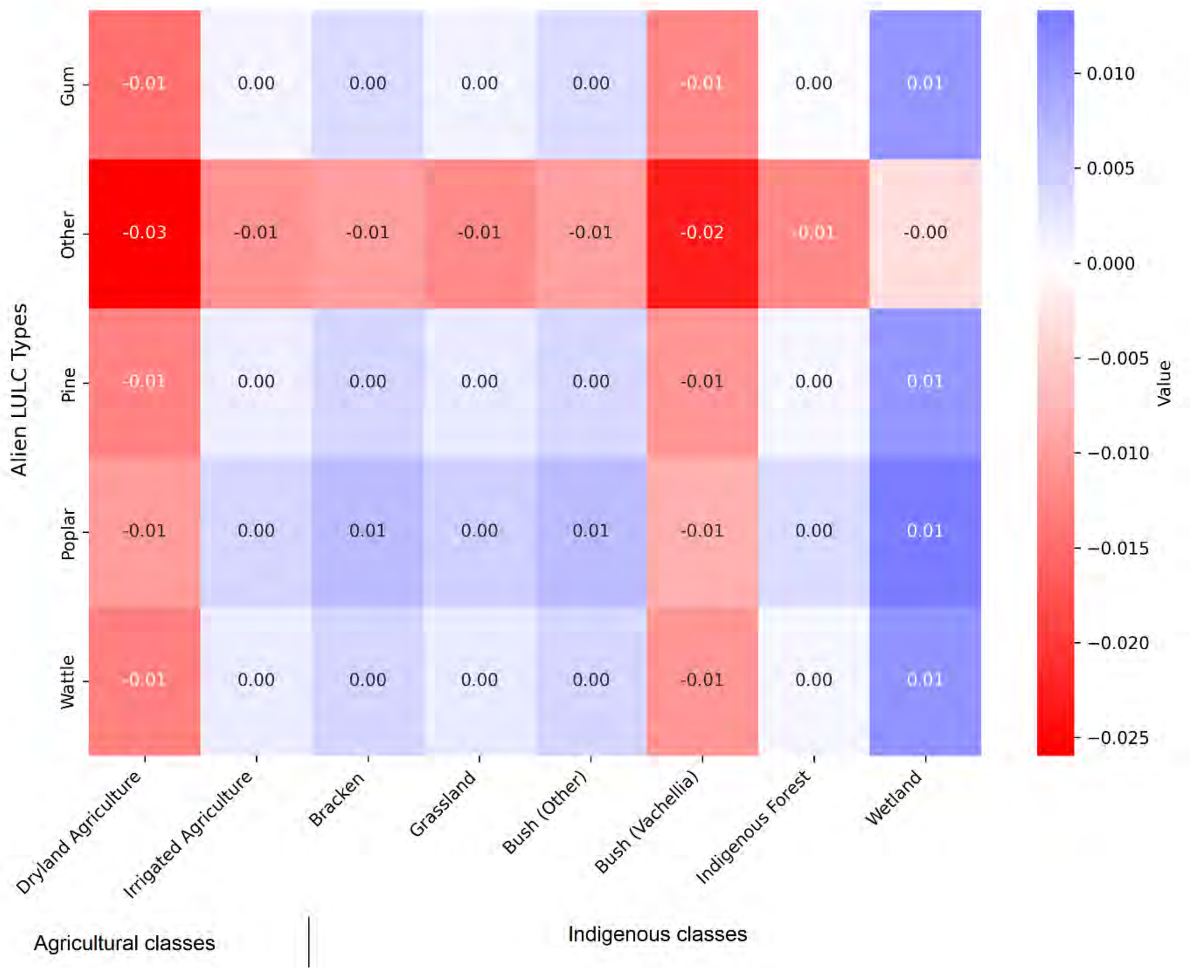


Figure 49. *A comparison of the different in the water-use factor between the surface water strategic water source area portion of the Tugela Catchment, and the entire catchment. Blue indicates higher water-use in the strategic water source area, red indicates higher water-use in the catchment, and white shows no difference.*

Potential water savings with invasive alien tree clearing
Relative and linear (mm/a) water-use impacts (i.e. differences in evapotranspiration) are interesting theoretically. However in practice, if there are only small woody alien plant invasions, then the water impact will be small. Likewise, if there are large areas of invasion, the potential water impacts of clearing will be larger. Therefore it is important to understand the area of invasion, and calculate the potential volumes of water that may be released if these invasions are cleared, to quantify actual water impact.

There is hardly any pine in the Tugela Catchment, only scattered emergent invasions in the mountains which could become a major issue later if left to spread (**Table 35**). Hence there is little potential water benefit in terms of volume released with clearing. Likewise the poplar invasions in the Tugela are in narrow strips along rivers, and due to small area coverage, have limited water volume benefits at a catchment scale. However gum plantations and wattle invasions cover reasonably large areas, and their removal would result in significant water volumes being released if being replaced with indigenous vegetation (restoration) or rainfed agriculture.

Table 35. *The potential volume of water that could be generated from clearing woody invasive alien plants within the Tugela Catchment, South Africa (in million m^3). These values represent only alien tree invasions, and not plantations. Blue indicates gains, and red losses in volume. Conversion: 1 million m^3 is equivalent to 400 Olympic-sized swimming pools.*

	Gum	Other	Pine	Poplar	Wattle
Bracken	0.3	0.6	0.2	0.5	2.3
Grassland	0.4	0.7	0.2	0.5	2.4
Bush (Other)	0.3	0.1	0.1	0.3	1.7
Bush (Vachellia)	0.2	-0.9	0.0	0.0	0.5
Indigenous Forest	0.2	-0.7	0.0	0.1	0.7
Wetland	0.3	0.2	0.1	0.4	1.8
Dryland Agriculture	0.4	1.0	0.2	0.6	2.7
Irrigated Agriculture	0.2	-1.2	0.0	-0.1	0.1

5.4.4. uMzimvubu Catchment

In the uMzimvubu Catchment, woody invasive alien trees have similar water-use to indigenous bush, but higher than other indigenous classes, such as grassland and wetlands (**Table 36**, **Figure 50**). Black/Green Wattle invasions are the highest water user, with higher water-use relative to Silver Wattle invasions.

Table 36. *Statistics for evapotranspiration (ET) for the last five years (2019-2023) for each land-use/land-cover (LULC) class for the uMzimvubu Catchment, South Africa (mm/a).*

Category	Class	Minimum	Maximum	Range	Mean	St Dev
Alien	Black/Green Wattle	571.9	1035.4	463.5	770.2	77.2
	Silver Wattle	556.1	1013.4	457.2	747.7	87.3
	Gum	563.1	1011.8	448.7	740.1	71.0
	Pine	551.5	1008.1	456.5	750.8	58.0
	Poplar	539.3	921.0	381.6	686.9	52.7
	Other	528.3	1013.7	485.4	738.3	78.8
Agriculture	Dryland Agriculture	513.8	995.0	481.2	681.6	68.3
	Irrigated Agriculture	519.4	1022.4	503.0	767.6	85.4
	Maize	513.8	986.0	472.1	650.0	48.9
Indigenous	Grassland	523.3	948.9	425.5	663.4	38.0
	Bush	532.4	1008.3	475.9	741.9	70.2
	Wetland	498.8	996.7	497.8	664.4	45.6
Other	Bare Ground	498.8	1014.4	515.6	623.1	47.3
	Urban	502.3	1021.7	519.4	646.1	48.9
	Water	499.4	1010.0	510.6	701.7	79.4

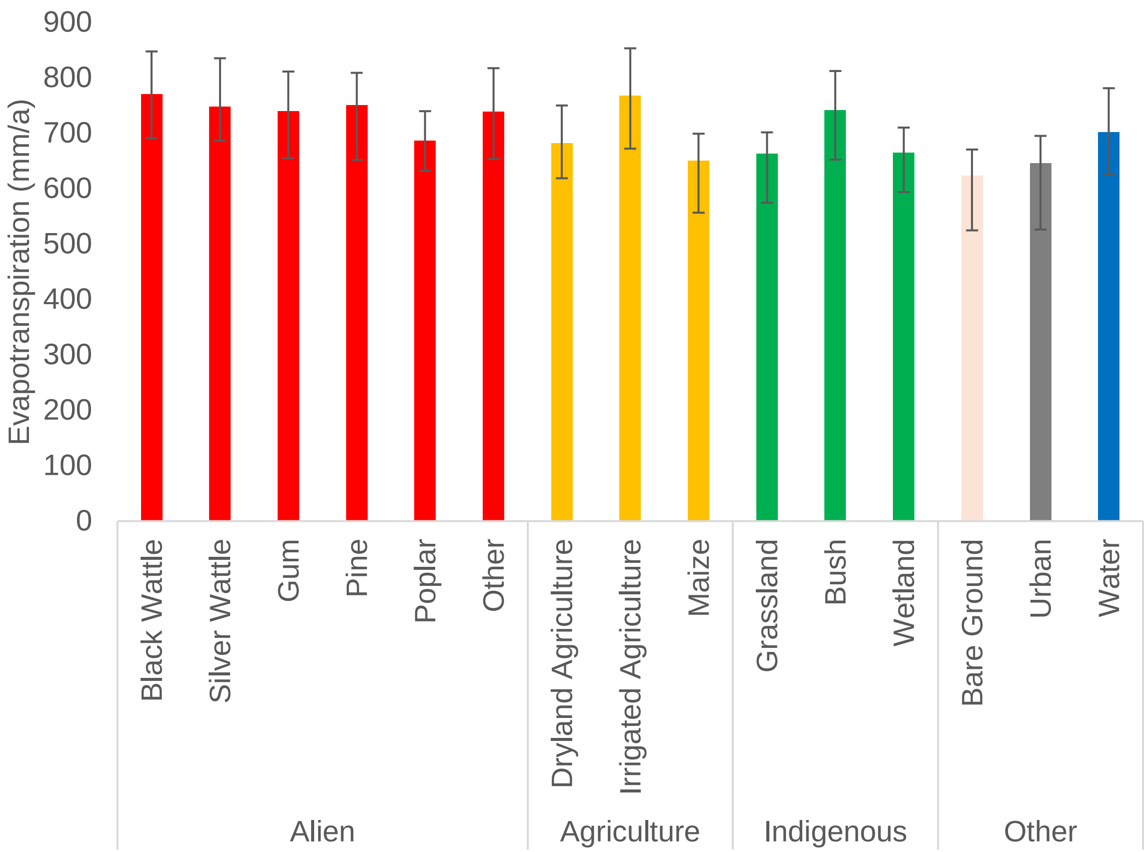


Figure 50. *Mean (±standard deviation) evapotranspiration (mm/a) for the last five years (2019-2023) for each land-use/land-cover (LULC) class for the uMzimvubu Catchment, South Africa.*

Relative water-use

It is important to consider that if the purpose of invasive alien tree clearing is to restore indigenous classes, then the most appropriate class should be considered, relative to a reference ecosystem (i.e. whether the comparison is to indigenous forest or bush is pre-determined by ecological factors). If the decision to be made is to consider a shift from a plantation to a different crop, for example banana or nuts, then there is more freedom of selection, although there will be soil and microclimate factors to consider as well (which is out of the scope of this research). Therefore the following tables only show the relative water gains associated with a land-use change, with no other factors considered and should not be applied without ecological and agricultural expertise as applicable.

A shift from woody invasive alien plants to almost any other land-use/land-cover class in the uMzimvubu results in an increase in water, except for a transition to irrigated agriculture and bush (**Figure 51**, **Figure 52**).

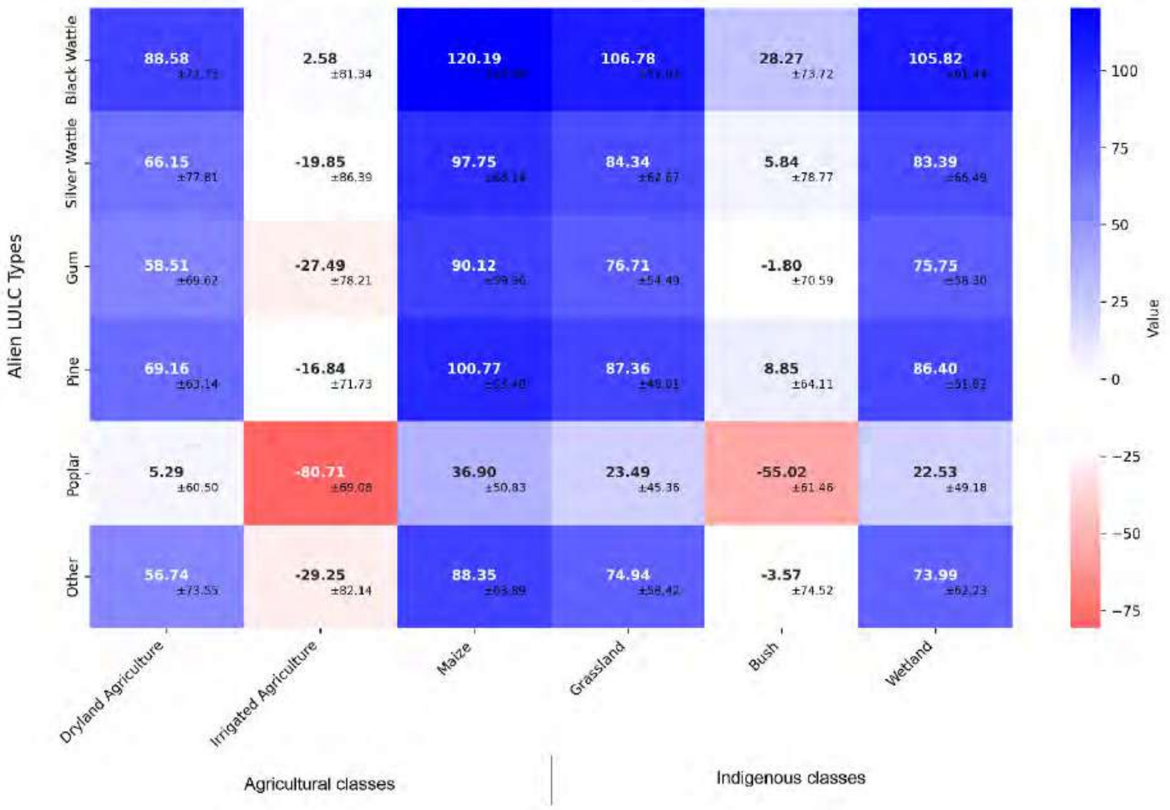


Figure 51. *The relative water-use (mm/a) for some key land-use/land-cover classes for the uMzimvubu Catchment, South Africa. Water gains are in blue, losses in red, and no change in white.*

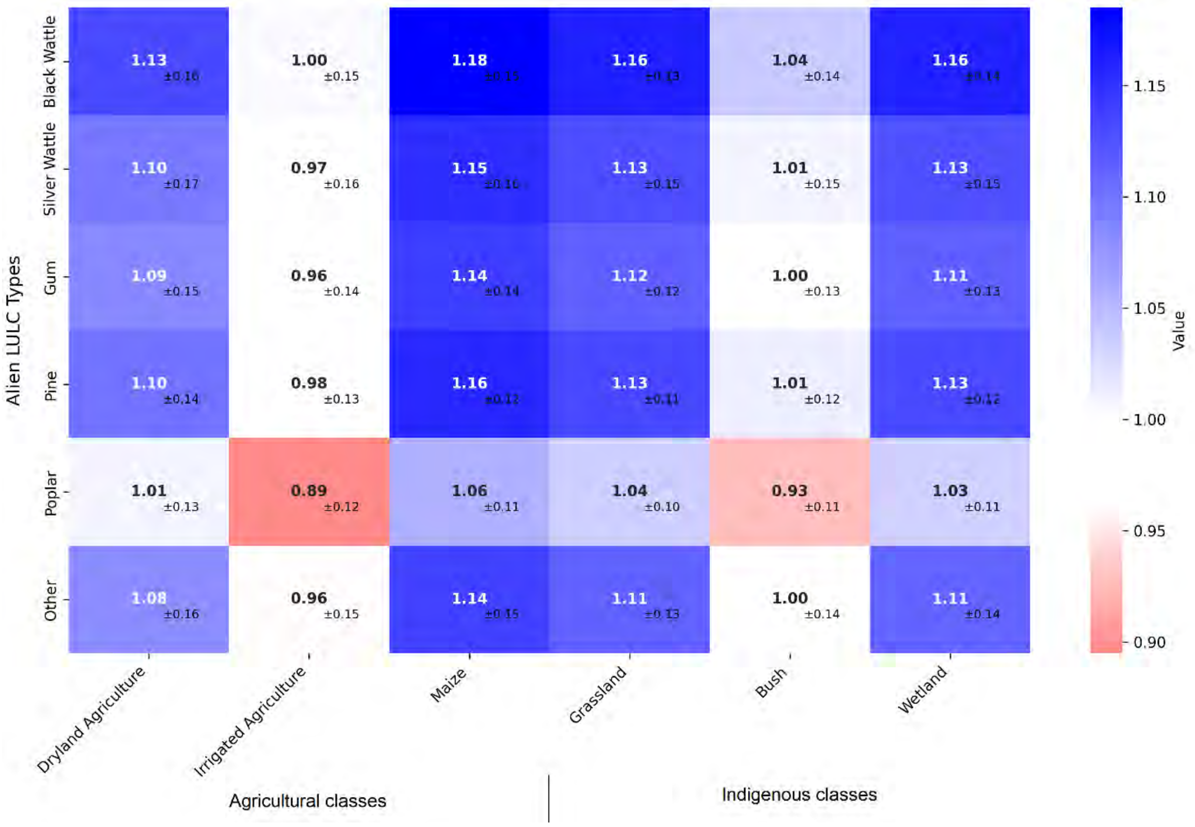


Figure 52. *The water-use factor with which to multiply evapotranspiration to understand potential water-related impacts of land-use or land-cover change for the uMzimvubu Catchment, South Africa. Water gains are in blue, losses in red, and no change in white.*

Evapotranspiration inside and outside of strategic water source areas

In the uMzimvubu Catchment there is hardly any difference in water-use factor (i.e. the ratio among different land-use/land-cover classes) inside and outside the surface water strategic water source areas (**Figure 53**). It is possible that a shift from woody invasive alien plants to bush inside the surface water strategic water source area would result in slightly more water released relative to outside this strategic water source area, however the magnitude of this difference is small (0.02-0.06).

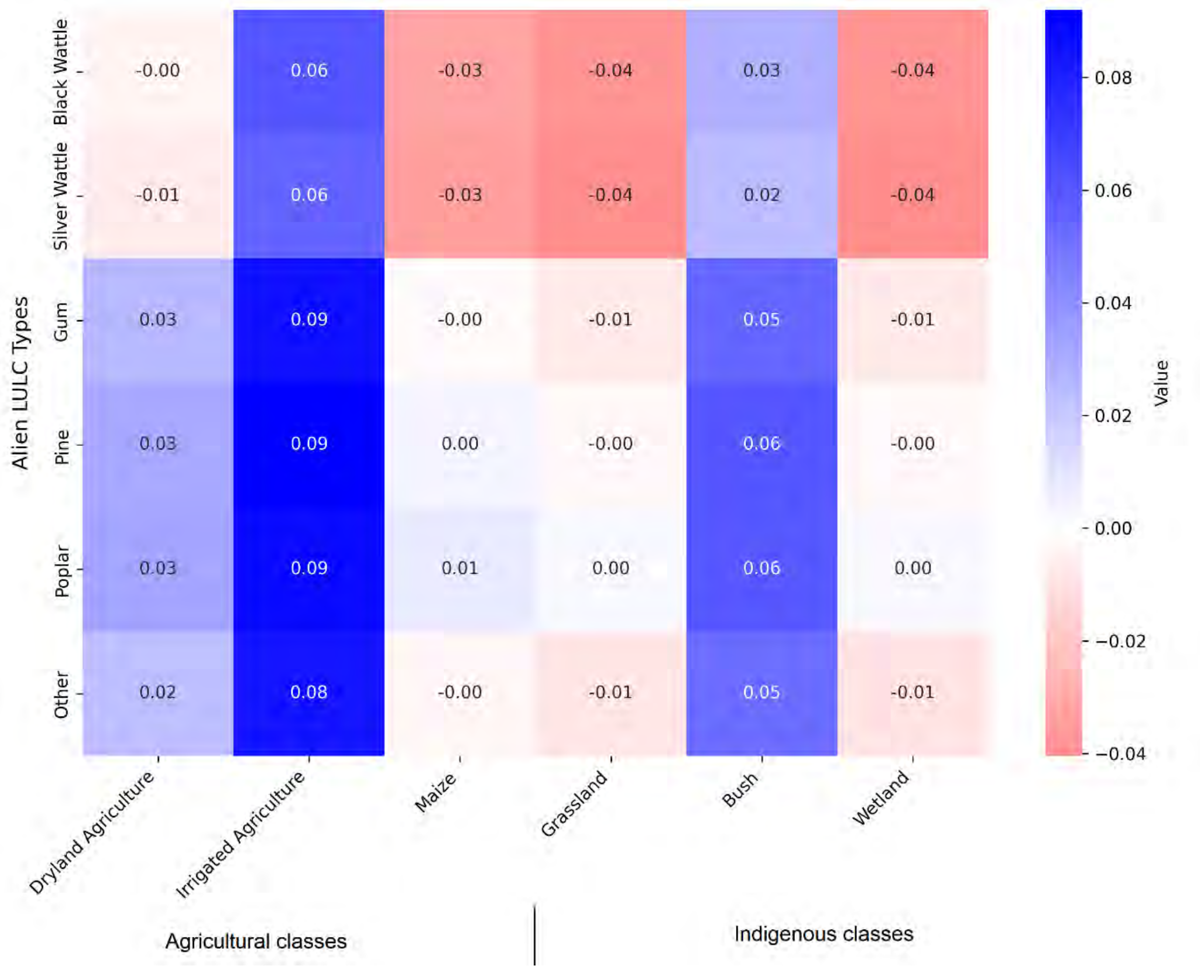


__Figure 53.__ A comparison of the different in the water-use factor between the surface water strategic water source area portion of the uMzimvubu Catchment, and the entire catchment. Blue indicates higher water-use in the strategic water source area, red indicates higher water-use in the catchment, and white shows no difference.

Potential water savings with invasive alien tree clearing

Relative and linear (mm/a) water-use impacts (i.e. differences in evapotranspiration) are interesting theoretically. However in practice, if there are only small woody alien plant invasions, then the water impact will be small. Likewise, if there are large areas of invasion, the potential water impacts of clearing will be larger. Therefore it is important to understand the area of invasion, and calculate the potential volumes of water that may be released if these invasions are cleared, to quantify actual water impact.

In the uMzimvubu Catchment, gum and pine are commercial plantations or woodlots whereas the wattle (Black/Green and Silver Wattle) is mainly invasions with some woodlots. There are potentially very large water benefits if all the Black/Green and Silver Wattle are cleared, cumulatively 76 million m^3 if they are restored to grassland and wetlands, which they have invaded (**Table 37**).

Table 37. *The potential volume of water that could be generated from clearing woody alien plant invasions within the uMzimvubu Catchment, South Africa (in million m^3). These values represent only alien tree invasions, and not plantations. Blue indicates gains, and red losses in volume. Conversion: 1 million m^3 is equivalent to 400 Olympic-sized swimming pools.*

	Black /Green Wattle	**Silver Wattle**	**Gum**	**Pine**	**Poplar**	**Other**
Grassland	30.0	37.2	9.4	4.2	1.2	2.0
Bush	7.9	2.6	-0.2	0.4	-2.8	-0.1
Wetland	29.7	36.8	9.3	4.2	1.1	2.0
Dryland Agriculture	24.8	29.2	7.2	3.3	0.3	1.5
Irrigated Agriculture	0.7	-8.8	-3.4	-0.8	-4.1	-0.8
Maize	33.7	43.2	11.0	4.9	1.9	2.4

5.4.5. Comparison to the literature

5.4.5.1. Absolute evapotranspiration

There is a weak correlation between the evapotranspiration estimated for various woody invasive alien plant classes in this study compared to the literature (**Figure 54**, **Table 38**). Additionally, the evapotranspiration estimates in this study are consistently lower than that reported in literature. The mean ratio of evapotranspiration estimates to evapotranspiration from literature is 1:1.4. A mean percentage bias of -15.47% was found when comparing evapotranspiration estimates to that of the 14 flux towers (Cogill et al. 2025). However what is key to consider, is that MAPWAPS measures water use over both invasions and plantations, while research has shown that plantations may use less water relative to invasions (Meijninger and Jarmain 2014). Additionally the literature (**Table 39**) uses a diversity of different approaches to estimate evapotranspiration, from sap flow (stem scale) through flux towers of varying types, to remote sensing, as well as many different measures (e.g. evaporation, transpiration and evapotranspiration). This makes it harder to make direct comparisons. Due to the potentially underestimated evapotranspiration for South Africa, one option could be to calibrate the evapotranspiration algorithm, but then one risks over-fitting the model with limited transferability elsewhere. Regardless of whether the absolute values are accurate or not, the strength of this method is that it is possible to obtain spatial information and to calculate relative water-use among classes.

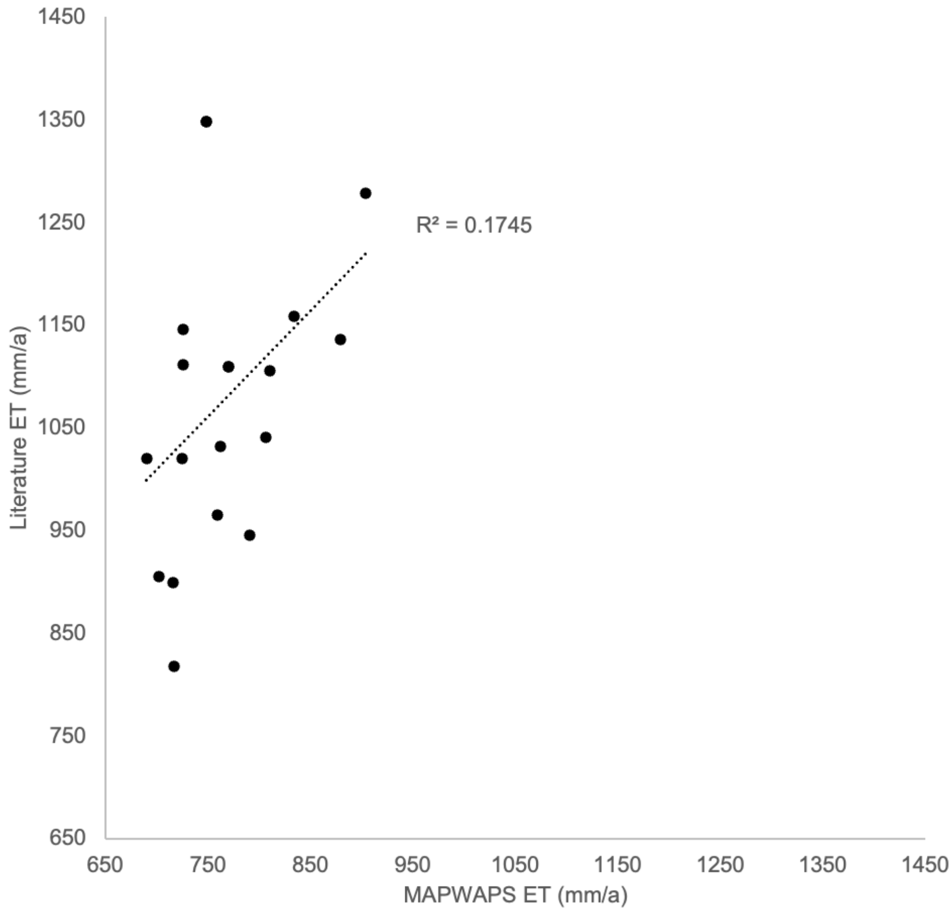


Figure 54. *A comparison of the evapotranspiration (ET) estimates derived in MAPWAPS to that of the literature for South Africa. Data are based on **Table 38**.*

Table 38. *The relationship between the MAPWAPS-derived evapotranspiration estimates (mm/a) and the literature by catchment where possible, and otherwise overall in South Africa. For full details and references, such as equipment/techniques used, refer to* ***Table 39****.*

	Tugela		**Luvuvhu**		**Sabie-Crocodile**		**uMzimvubu**		**Overall**		**Literature**
	MAPWAPS	**Literature**	**MAPWAPS**	**Literature**	**MAPWAPS**	**Literature**	**MAPWAPS**	**Literature**	**MAPWAPS**	**Literature**	
Wattle	726	1111							726	1145	*A. mearnsii, A. saligna, A. longifolia, A. dealbata, A. decurrens* in the Western Cape, Eastern Cape, and KZN (Burger, 1999; Clulow, 2007; Clulow et al., 2011; Dye et al., 2001; Dye and Jarmain, 2004; Dye et al., 2008; Le Maitre et al., 2019; Meijninger and Jarmain, 2014; Palmer et al., 2023)
Black Wattle							770	1109	770	1109	*A. mearnsii,* in the Western Cape and KZN (Dye et al. 2001; Dye and Jarmain 2004; Clulow 2007; Clulow et al. 2011; Meijninger and Jarmain 2014; Le Maitre et al. 2019)
Silver Wattle							748	1348	748	1348	*A. dealbata* in the Eastern Cape (Palmer et al. 2023b)
Gum	762	1032	834	1159	904	1278	740	-	810	1106	Gum spp (*E. grandis and E. camaldulensis*) in the Western Cape, Limpopo, Mpumalanga and KZN (Burger, 1999; Dye, 1996; Dye et al., 2008; Dzikiti et al., 2016; Le Maitre et al., 2019; Meijninger and Jarmain, 2014; Scott et al., 2000)
Poplar	717	818					687		702	905	Poplar spp (*P. canescens and P. deltoides*) in the Western Cape and KZN (Dye et al., 2008; Le Maitre et al., 2019; Ntshidi et al., 2018)
Lantana			735		783				759	965	*Lantana camara* in KZN (Meijninger and Jarmain 2014)
Bugweed			767		813				790	945	*Solanum mauritianum* in KZN (Meijninger and Jarmain 2014)
Pine	716	899	881		879	1136	751		806	1041	Pine spp (*P. radiata, P. pinaster, P. patula, and P. halepensis*) in the Western Cape, KZN, Mpumalanga and Swaziland (Dye et al., 2008; Dzikiti et al., 2013; Le Maitre et al., 2000; Meijninger and Jarmain, 2014; Scott, 1999; Scott et al., 2000)
Yellow Bells					760				760	-	No literature for this in South Africa
Other Aliens	690	1020	659		810		738		725	1020	*Chromolaena odorata* and Triffid Weed in KZN (Meijninger and Jarmain 2014)

Table 39. *Water-use of key woody invasive alien plants in South Africa according to the literature.*

Genus/ LULC	Paper	Method	Region	Water-use
Pine	Dye et al., 2008	Annual transpiration: Measured with HPV	Usutu, Swaziland	944 mm
	Dzikiti et al. 2013	Annual ET: HPV method with surface energy balance using heat flux data from LAS for *P pinaster* and *P halepensis*	Simonsberg Mountains, Western Cape	1190 mm non-riparian 1417 mm riparian
	Le Maitre et al., 2000	Mean water use in Mm^3: Streamflow reduction	Across SA	231.53 Mm^3
	Scott et al. 2000	Evaporation: Catchment gauging – *P patula* *P. patula* *P. radiata* Evaporation from water balance – *P. radiata*	Cathedral Peak, KZN Sabie, MPU Jonkershoek, W Cape Biesiesvlei, W Cape	1065 - 1143 mm 1136 mm 990 – 1136 mm 1057 mm
	Scott 1999	Streamflow increase after clearing measured in mm/ annum	Witklip, Sabie	1150 mm
	Cullis et al. 2007	Streamflow increase after clearing measured in m^3/ ha/ annum	Witklip, Sabie (non riparian) & Biesiesvlei, W Cape (riparian)	4045 m^3/ ha 11505 m^3/ ha
	Le Maitre et al., 1996	Streamflow reduction derived from van Wyk 1987 measured in mm for Fynbos afforested with Pinus radiata	Bosboukloof, Tierkloof, Biesiesvlei, Lambrechtsbos: W Cape	330 – 500 mm
	Gush et al. 2002	Flow reduction in mm/ annum using the ACRU model	Cathedral Peak, KZN Lambrechtsbos,	339 mm/ annum 241 mm/ annum
	Meijninger and Jarmain 2014	Annual average evaporation in mm based on WIMS: Remote sensing approach	W Cape: Infestations W Cape: Plantations KZN: Plantations	915 mm/ annum 735 mm/ annum 650 mm/ annum

Wattle	Clulow et al. 2011	ET/ annum: LAS and PT model verification for *A mearnsii*	Two Streams Catchment (non-riparian), KZN	1156 mm (2007)
	Clulow 2007	Scintillometry: Annual Evaporation in mm	Seven Oaks (non-riparian plantation), KZN	1171 mm
	Dye and Jarmain 2004	HPV: Annual Evaporation in mm Bowen ratio: Annual Evaporation in mm	Gilboa (riparian), KZN Seven Oaks (non-riparian), KZN	1260 mm 1048 – 1364 mm
	Dye et al. 2001	ET mm/ annum: Bowen ratio – energy balance	Fynbos, Western Cape Grassland, Western Cape - Jonkershoek	Difference = 171 mm Difference = 424 mm [*A.mearnsii*: 1503 mm]
	Meijninger and Jarmain 2014	ET mm/ annum: Remote sensing approach and based on WIMS	W Cape KZN KZN: Plantations	925 mm 740 mm 615 mm
	Dye et al., 2008	ET mm/ annum: WAVES simulation: EC, BR, HPV, LAS Annual transpiration	Wellington, W Cape Seven Oaks, KZN	1165 mm 1062-1118 mm (simulated) 1239-1364 mm (BR)
	Everson et al., 2007	Streamflow increase after *A. mearnsii* clearing	Two Streams, KZN Dryland Riparian	 5.62 m^3/ ha/ annum 6.47 m^3/ ha/ annum
	Burger 1999	ET/ annum	Seven Oaks plantation, KZN	1048 – 1346 mm/ annum
	Le Maitre et al., 2000	Streamflow reduction in Mm^3	Across SA: *A. mearnsii* *A. dealbata* *A. decurrens*	 576.58 Mm^3 248.32 Mm^3 9.83 Mm^3
	Le Maitre et al. 2019	Evaporation (mm/ annum): Estimated from eLeaf database	Berg River tributaries:	 1310 mm

			A. mearnsii *A. saligna* *A. longifolia*	1155 mm 1283 mm
	Palmer et al. 2023b	ET (mm/ annum): MEDRUSH	*A dealbata* - Albany Thicket, Eastern Cape	1348 mm vs 509 mm (uninvaded grassland)
	Scott-Shaw and Everson, 2017	L per ha / annum: Upscaled HPV for *A. mearnsii*	Buffeljags River, W Cape	5.85 ML/ha/ a
	Scott-Shaw and Everson, 2019	L/ annum: Upscaled sap flow data for *A. mearnsii*	New Forest Farm, KZN	5786 – 7310 L/ annum
	Rowntree and Beyers 1999	Streamflow reduction in m^3/ha/ annum for *A. mearnsii*	Sand River	4964 m^3/ha = 496 mm
Gum	Dye et al, 2008	Annual transpiration for *Euc grandis*	Sabie, MPU	1347 mm
	Dzikiti et al. 2016	ET/ annum: SEBAL and MOD16	Hermon, Berg River Catchment	1058 mm vs 865 mm cleared (SEBAL) 1039 mm vs 804 mm (MOD16)
	Le Maitre et al. 2000	Streamflow reduction	Across SA	213.98 Mm^3
	Le Maitre et al. 2019	Evaporation mm/ annum for *E. camaldulensis*	Berg River tributaries	1347 mm
	Scott-Shaw and Everson, 2019	Upscaled sap flow data in L/ annum for *E grandis*	New Forest Farm, KZN	5785 – 7310 L/ annum
	Gush et al. 2002	Mean flow reduction: ACRU model in mm/ annum	Wesfalia	291 mm/ annum
	Meijninger and Jarmain 2014	Evaporation mm/ annum: Remote sensing approach and based on WIMS	W Cape KZN invasion: KZN plantations:	945 mm 575 mm 690 mm
	Burger 1999	Annual Evaporation: Bowen ratio for Euc plantations	Seven Oaks, KZN	1246 – 1618 mm
	Scott et al. 2000	Annual evaporation: Catchment gauging for E. grandis	Tzaneen, Limpopo Sabie, MPU	1159 mm 1140 mm
	Dye 1996	Transpiration mm/ annum : Sap flow for *E. grandis*	Sabie, MPU	1347
Poplar	Dye et al., 2008	Annual Transpiration for *P. deltoides*	Greytown, KZN	818 mm

	Le Maitre et al. 2000	Streamflow reduction: Mm^3	Across SA	53.83 Mm^3
	Le Maitre et al. 2019	Annual evaporation (mm/ annum) from eLeaf database for *P. canescens*	Berg River tributaries	1277 mm/ annum
	Ntshidi et al. 2018	Transpiration: Scholander type pressure chamber for *P. canescens*	Riparian zone in Franschoek, W Cape	620 mm (large trees) 338 mm (smaller trees)
Lantana camara	Meijninger and Jarmain 2014	Evaporation mm/ annum: Remote sensing approach and based on WIMS	KZN	965 mm
	Le Maitre et al. 2000	Mm^3: Streamflow reduction	Across SA	97.14 Mm^3
Chromolaena odorata	Meijninger and Jarmain 2014	Evaporation mm/ annum: Remote sensing approach and based on WIMS	KZN	1020 mm
Bugweed	Meijninger and Jarmain 2014	Evaporation mm/ annum: Remote sensing approach and based on WIMS	KZN	945 mm
	Le Maitre et al. 2000	Mm^3: Streamflow reduction	Across SA	139.97 Mm^3
Mopane	Aldworth et al. 2022	Total annual ET: Surface renewal for Mopane dominated Savanna bush	Mthimkhulu, Limpopo	655 mm (2019-2020) 580 mm (2021-2022)
Grassland	Clulow et al. 2012	Total annual ET: Surface renewal for Seasonal grassland at Maputaland Coastal Plain	Embomveni, Maputaland Coastal Plain, KZN	487 mm
	Dye et al. 2001	Bowen ratio – energy balance	KZN	836 mm
	Dye et al., 2008	ET mm/ annum:	Drakensberg Catchment sites	592-863 mm
	Everson et al. 2011	Evaporation mm/ annum		695 mm
	Schulze 1979	ET mm/ annum for grasslands	Midlands and Drakensberg, KZN	600 – 860 mm
	Palmer et al. 2023b	ET mm/ annum: using MEDRUSH	Albany Thicket, E Cape	509 mm

	Meijninger and Jarmain 2014	Evaporation mm/ annum: Remote sensing approach and based on WIMS	KZN	640 mm
	Everson et al. 1998	Evaporation mm/ annum: Bowen ratio for moist upland grassland	Cathedral Peak, KZN	651 – 752 mm
	Savage et al., 2004	Evaporation in mm/annum: Scintillometry	Midlands, KZN	673 mm
	Dye et al., 2008	Bowen ratio	Midlands, KZN	651 mm
Savanna	Meijninger and Jarmain 2014	Evaporation mm/ annum: Remote sensing approach and based on WIMS	KZN	685 mm
	Dye et al., 2008		Nylsvley	469 mm
	Dzikiti et al. 2019	ET/ annum: Eddy covariance	Skukuza	610 mm
	Palmer and Yunusa 2011	ET/ annum: Regression model using MODIS fpar data and ET0 for arid Savanna	Riemvasmaak	119 mm
	Palmer et al. 2015	ET mm/ annum using modelling approach with MODIS LAI and ET0 for semi arid Savanna	Skukuza	378 mm
Indigenous Forest	Meijninger and Jarmain 2014	Evaporation mm/ annum: Remote sensing approach and based on WIMS	KZN W Cape	680 mm 1000 mm
	Dye et al., 2008	ET/ annum for Podocarpus forest	Groenkop Saasveld	1175 mm
	Everson et al. 2011	Evaporation mm/ annum		933 mm
	Le Maitre et al. 2019	ET mm/ annum using the eLeaf: Indigenous riparian montane	Berg river tributaries, W Cape	1037 mm
	Scott-Shaw and Everson, 2017	ET/ annum upscaled from HPV sap flow technique for indigenous riparian forest	Buffeljags River, W Cape	1.01 ML/ ha/ annum
	Scott-Shaw and Everson, 2019	Sap flow in L/ annum upscaled for: *S pyroides* and *G buxifolia* Additionally, for: *L sericea, C africana* and *K africana*	New Forest Farm, KZN	1639 – 3901 L/ annum 2369 – 4307 L/ annum
Valley Thicket	Meijninger and Jarmain 2014	Evaporation mm/ annum: Remote sensing approach and based on WIMS	KZN	755 mm
	Dye et al., 2008	Evaporation mm/ annum	Noodsberg, KZN	668 mm
Wetlands	Dye et al., 2008	ET/ annum for Phragmites wetlands	Orkney	1174 mm

	Le Maitre et al. 2019	Total annual evaporation using eLeaf data for indigenous riparian lowland	Hermon	820 mm
Albany Thicket	Gwate et al., 2016	ET mm/ annum: Surface conductance – Penman Monteith and MODIS data used	Ezulu, E Cape	288 mm

5.4.5.2. Relative evapotranspiration

There are few studies that have made direct comparisons of the water use (evapotranspiration) of native compared to invasive alien species (Dye et al. 2001, Dye et al., 2008, Le Maitre et al. 2019, Meijninger and Jarmain 2014, Palmer et al. 2023b). Often these studies are comparing across different methodologies (Dye et al., 2008, Le Maitre et al. 2019), and sometimes the sites may be far apart geographically, making it difficult to draw clear conclusions (Dye et al., 2008). We synthesized the results of the five studies that make comparisons of the water use native compared to invasive alien species, despite these limitations (**Table 40**). We then compare these to our findings. It should be kept in mind that (i) the vastly different techniques used in the literature result in high variance of the means, and (ii) the sites are sometimes very different from those explored in this study. Nevertheless it is interesting to make the comparison. Overall results show a weak relationship between the mean relative evapotranspiration from literature compared to those derived in this project, and the relationship is also not 1:1 (**Figure 55**).

Table 40. *The mean relative evapotranspiration (mm/a) among various native and invasive alien classes according to the literature (synthesized from Table 39).*

	Grassland	**Fynbos**	**Forest**	**Wetland**
Wattle	449.2	171	36.3	220.4
Gum	325.1	-	94.88	350
Pine	151.5	-	-145	-230
Poplar	-	-	-58.5	50.5
Lantana camara	325	-	-	-
Bugweed	305	-	-	-

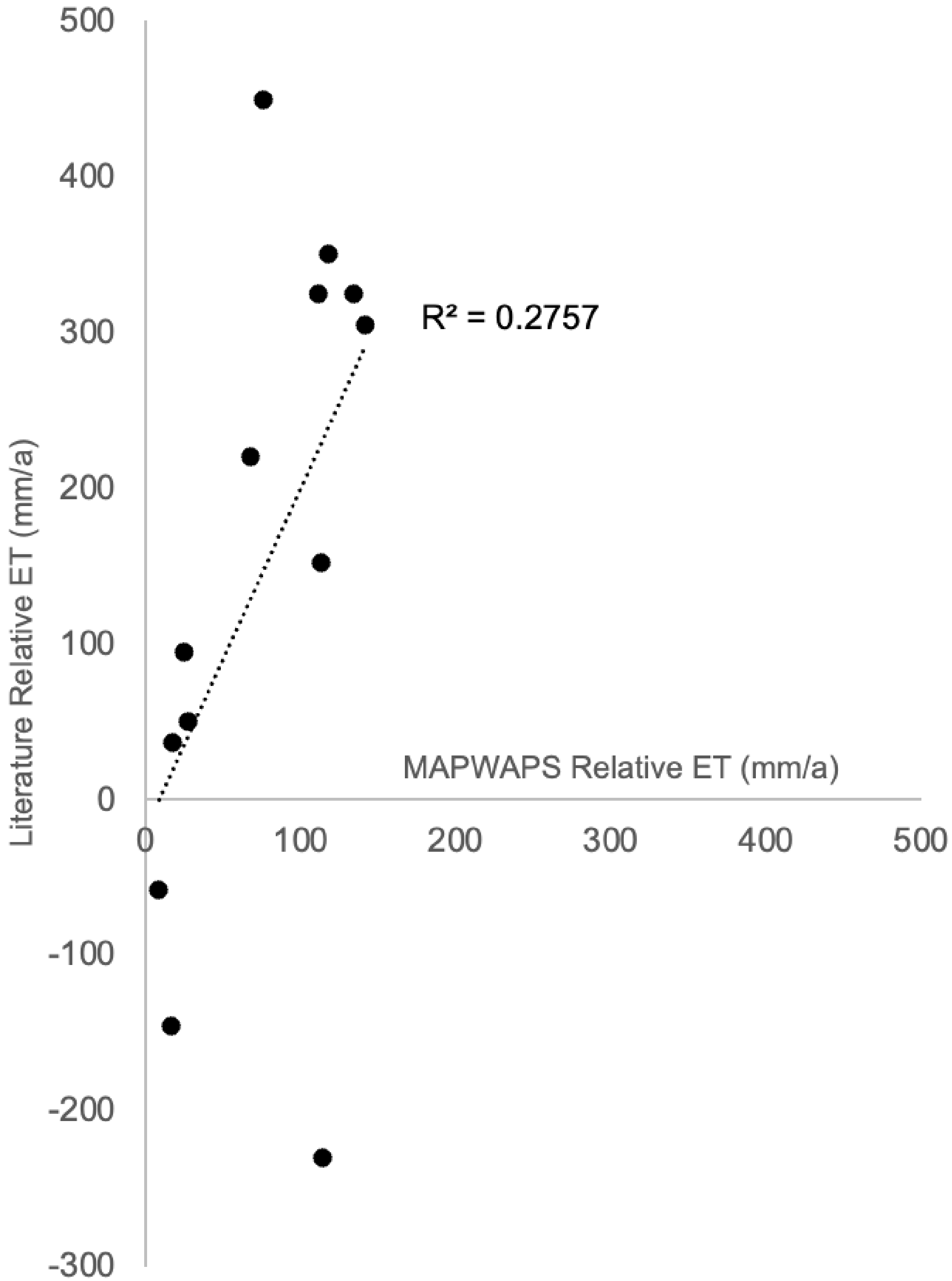


Figure 55. *The mean relative evapotranspiration (mm/a) among various native and invasive alien classes according to the literature as well as the MAPWAPS project.*

5.5. Practical application of the MapWAPS results for monitoring of woody alien plant invasions

5.5.1. Plantation Spread

Invasions of woody alien plants decrease in area with distance from plantations, with the highest relative area of invasion occurring within the first 100 m from the plantation blocks, declining with distance away from plantation blocks (**Figure 56**, **Figure 57**). This was true, regardless of taxon (i.e. whether it was the taxon planted in the plantation such as pine, wattle or gum, or taxa that are associated with plantations, such as Bugweed). These results demonstrate that plantations are a key source of woody invasive alien plants within these catchments, and warrants further, more detailed scientific investigation.

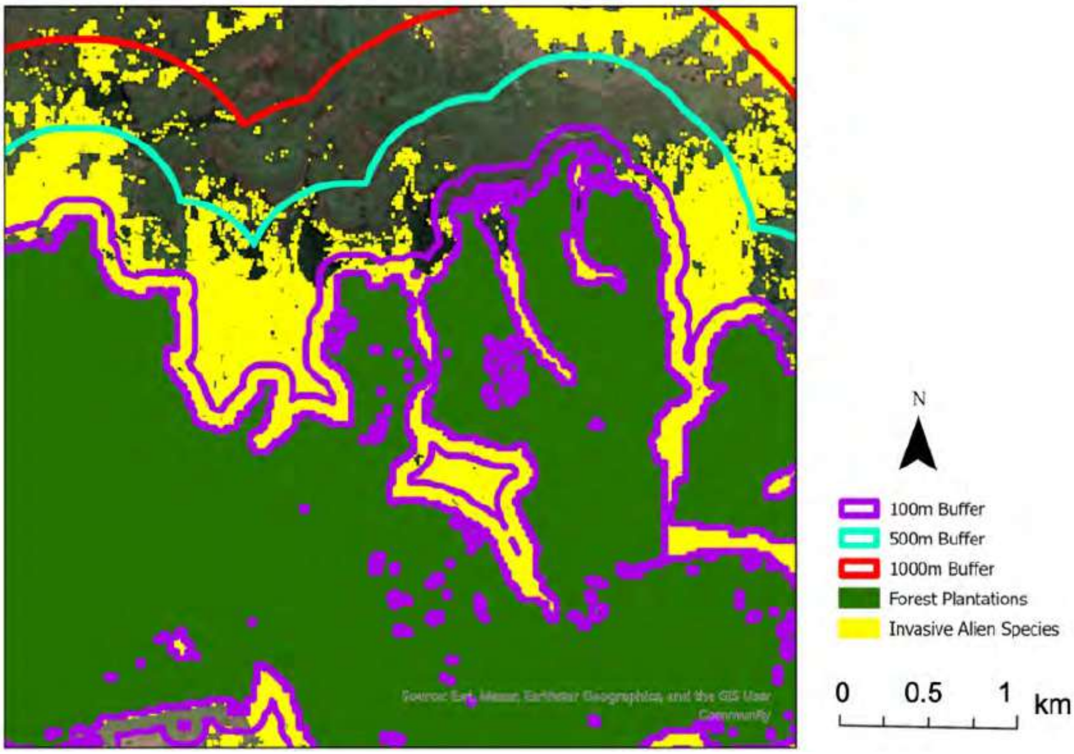


Figure 56. *Invasive alien tree spread from a plantation block (green) indicated in yellow within a 100 m buffer of the plantation, a 500 m buffer, and a 1000 m buffer from a plantation in the uMzimvubu Catchment, South Africa.*

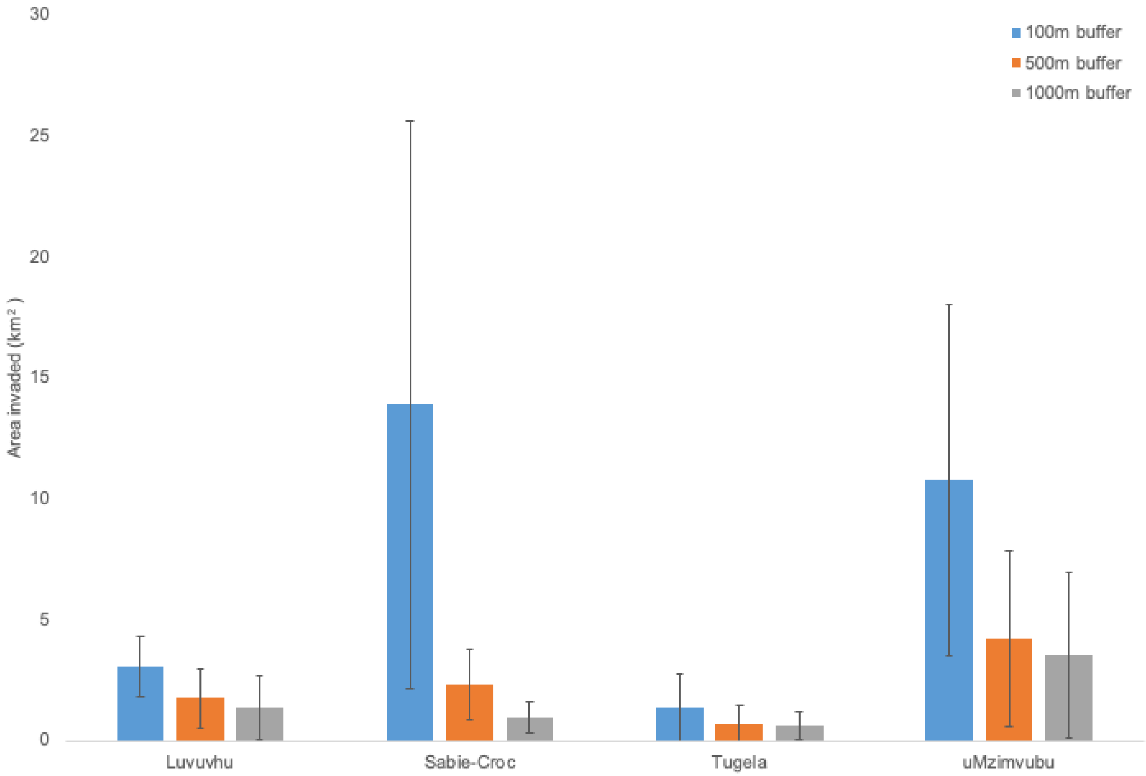


Figure 57. *The mean (± standard deviation) absolute change in invaded area with proximity (100 m, 500 m and 1000 m) to plantations taken from the national landcover map in each of the four catchments, South Africa.*

5.5.2. Plantation Compliance

If plantations exited from riparian zones and wetlands in the study catchments, a significant amount of water would be made available, particularly in the Sabie-Crocodile Catchment (2.5-3.0 million m^3 per annum) (**Table 41**). In all catchments, plantation forests were observed to be non-compliant, where plantations extend right up to the edges of, or through rivers and wetlands, leaving no buffer. This analysis looks at rivers alone (not even wetlands), and collectively for all four catchments plantations in riparian zones amount to an area of almost 30 km^2.

Table 41. *The relative volumes of water that could be freed up with an exit of plantation forestry from riparian zones (defined as a buffer of 50 m from the centre of the river). Mcm = millions of cubic meters.*

			Water released with conversion of:		Volume of water made available with removal of:	
Catchment	**Area (km^2)**	**Area (%)**	**Gum plantations to wetland (mm)**	**Pine plantations to wetland (mm)**	**Gum (mcm)**	**Pine (mcm)**
Luvuvhu	2.0	2.5	166.2	212.8	0.33	0.42
Sabie-Crocodile	19.4	18.7	152.1	126.92	2.95	2.46
Tugela	5.9	4.1	77.3	30.82	0.45	0.18
uMzimvubu	0.9	0.2	75.75	86.4	0.07	0.07

Besides plantations, the riparian zones are also invaded by plantation forestry escapees, amounting to an area of 76 km^2 for all four catchments collectively (**Table 42**). Likewise, the water gains for clearing riparian invasions of woody plants are substantial, and are the highest in the uMzimvubu Catchment (4.3-4.9 million m^3 per annum). On average for all four catchments, riparian zones are 14% covered by invasive alien trees, either as plantations or invasions.

Table 42. *The relative volumes of water that could be freed up with alien tree clearing within riparian zones alone (defined as a buffer of 50 m from the centre of the river). Mcm = millions of cubic meters.*

			Water released with conversion of:		Volume of water made available with removal of:	
Catchment	**Area (km^2)**	**Area (%)**	**Gum invasions to wetland (mm)**	**Pine invasions to wetland (mm)**	**Gum (mcm)**	**Pine (mcm)**
Luvuvhu	2.9	3.8	166.2	212.8	0.5	0.6
Sabie-Crocodile	10.0	9.7	152.1	126.92	1.5	1.3
Tugela	5.8	4.0	77.3	30.82	0.4	0.2
uMzimvubu	57.1	13.7	75.75	86.4	4.3	4.9

6. SYNTHESIS

This project has demonstrated how to successfully apply a methodology developed for mapping woody invasive alien plants cheaply, at a 10m spatial resolution, using freely available remote sensing imagery and cloud computing, achieving high accuracies (>94%) across a range of previously unstudied bioclimates and regions. Additionally, this project develops and validates a model to estimate an ensemble of evapotranspiration estimates spatially for South Africa at a 1-month timestep and 100 m resolution. The MapWAPS Project has demonstrated that the approach originally developed in the Fynbos Biome by Holden and Rebelo et al. 2021 is highly adaptable and performs well in multiple other biomes. These findings suggest that this approach could feasibly be used to develop a national woody invasive alien plant map that is both cost-effective and easily repeatable.

6.1. Recommendations for management

Clearing woody invasive alien plants in strategic water source area catchments has major water benefits. This project focusses only on the quantification of water-related benefits, however there are also co-benefits of clearing woody invasive alien plants, especially when this is done within an ecological restoration framework (e.g. restoration to grasslands, fynbos, savannas, bushveld). Some of the co-benefits relate to water regulation of healthy ecosystems, for example not only making water available, but also in the right season due to an increase in infiltration. This makes more water available in the dry season/years rather than in the wet season. This has benefits for attenuating downstream flooding and is a critical strategy for climate change adaptation. The longer we can keep water in the ecosystem, the more time for infiltration and related co-benefits. Furthermore, ecological restoration builds resilience and could contribute to securing the surface water strategic water source areas via adaptive, implementation, enabling mechanisms.

Besides the issue of woody invasive alien plants, the presence of plantations within strategic water source area catchments presents a trade-off: these plantations have economic benefits, but we have demonstrated that they also have a major water cost relative to native ecosystems. While this is not a new finding in South Africa’s long history of water resource research, this is the first study that has allowed detailed spatial comparison and quantification of relative water-use. Therefore, it is highly recommended that within certain surface water strategic water source areas, rezoning of land-use activities to more water-sensitive agriculture/forestry could be beneficial, or at the very least the cessation of licensing for further plantations. Genus swapping could also be considered for regions where certain taxa use more water than others. For example in the Sabie-Crocodile and Tugela catchments, gum appeared to use more water than pine, all other things being equal.

One of the major anecdotal observations collecting training data in the field, was the issue of aliens invading from plantations. This is a matter that has been previously quantified (Mcconnachie et al. 2015), and should be urgently addressed by forestry, as it is a major threat to water security. In addition, the true cost of plantation forestry is not being accounted for in relation to any profit (and therefore viability), as the forestry sector is not required to take responsibility for spread from their plantations. There are several options, the first is that the clearing of spread of invasive alien plants from plantations should be enforced by government, and the second is that forestry invests into sterile cultivar alternatives, at which point the use of invasive alien species in plantations should be banned.

In the four study catchments forestry is not compliant in terms of avoiding planting into riparian buffer zones. If plantations exited from riparian zones (i.e. became compliant), a significant amount of water would be made available. Government could explore options to encourage and enforce this process and improve compliance nationally, for example via the Forest Stewardship Council (FSC) certification mechanism.

Another key recommendation is that sustainable investment (finance) into invasive alien tree clearing is critical. There needs to be a long-term, strategic vision and programme with collaboration from all sectors and stakeholders. This is critical as research has shown that previous piece-meal, uncoordinated investments have had questionable impacts ecologically (van Wilgen et al. 2022). Additionally, it is important that the methods applied are ecologically strategic to achieve success (e.g. applying best-practices such as working from the top of the catchment to the bottom, prioritizing sparse invasions over dense ones, using biological control, the correct and cautious use of herbicides, e.g. for cut stump treatment).

6.2. Opportunities for future research

Mapping woody invasive alien plants, even to species level, has been demonstrated in this project to be possible using Sentinel-2 data, free cloud computing, and machine learning algorithms. Given the high success and accuracies (>94%), particularly compared to currently used methods, investing in monitoring invasive alien trees in South Africa using remote sensing should be a national priority. When future research projects are conducted on invasive alien plant mapping, all data should be required to be made publicly available, especially including the training data. Training data collection is the most important and the most expensive part of this process.

This work presents the first step towards a better understanding of the relative water-use of various land-use/land-cover types in South Africa. However to take this work further and to be able to be confident about relative impact on water, the confounding variables will need to be accounted for. A causal inference approach could be used to study relative impact on water for different taxa (e.g. pines, gums or wattles) that could potentially have other characteristics that confound impacts. Some examples include growing only at certain altitudes, or in riparian zones.

The development of a tool to estimate water-use impacts of land-use/land-cover decisions using satellite remote sensing products would be critical to support decision-making and monitoring in water resource management. The most commonly used tool in South Africa currently only considers streamflow changes, and this alternative approach quantifies all changes in water availability, including groundwater and surface water, since the largest part of the water cycle is monitored (evapotranspiration). A free tool could support small-scale, emerging farmers, as well as assist non-profit entities to quantify the impacts of invasive alien tree clearing programmes.

6.3. Potential for value added outputs

The research developed within this WRC project, due to the study design, testing in various bioclimates as well as building on studies in other regions (Holden et al. 2021; Rebelo et al. 2021), has the potential for operational rollout at a national scale. Results of woody invasive alien plant mapping can feed into reporting on the National Biodiversity Assessment as well as reporting under the Global Biodiversity Targets, for example target 2, which is to restore 30% of degraded ecosystems by 2030. Therefore, it is recommended for reporting purposes that South Africa moves towards an annually produced national woody invasive alien plant map. Besides reporting, this will also be useful for monitoring clearing and compliance of implementers to contractual obligations and assessing the impact of investment into invasive alien plant clearing, evidence for which has been limiting to date (van Wilgen et al. 2022).

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APPENDICES

Appendix 1. Data access

To access the data for each of the study catchments, please use the following links:
MapWAPS Invasive Alien Plant map for the Tugela Catchment:
https://doi.org/10.25413/sun.25066151
MapWAPS Invasive Alien Plant map for the uMzimvubu Catchment:
https://doi.org/10.25413/sun.25050401
MapWAPS Invasive Alien Plant map for the Luvuvhu Catchment:
https://doi.org/10.25413/sun.25050314
MapWAPS Invasive Alien Plant map for the Sabie-Crocodile Catchment:
https://doi.org/10.25413/sun.25050368

To access the quick looks of the alien tree maps for each of the study catchments, please use the following links:
Luvuvhu Catchment: https://mapwaps-luvuvhu.projects.earthengine.app/view/mapwaps-luvuvhu
Sabie-Crocodile Catchment: https://mapwaps-sabiecroc.projects.earthengine.app/view/mapwaps-sabiecroc
Tugela Catchment: https://mapwaps-tugela.projects.earthengine.app/view/mapwaps-tugela
uMzimvubu Catchment: https://mapwaps-umzimvubu.projects.earthengine.app/view/mapwaps-umzimvubu

Appendix 2 Capacity building

Mr Liam Cogill was funded to do his PhD through the MAPWAPS project, titled: "Using advanced and integrative remote sensing applications to inform strategic woody invasive alien plant management in important catchments" from 2022-2025. He is supervised by Dr Alanna Rebelo and Prof Karen Esler.

Ms Thandeka Skosana was funded to do her MSc through the MAPWAPS project, titled: "*Using Remote Sensing Techniques to Detect Woody Invasive Alien Plants in Strategic Water Source Areas*" from 2022-2025. She is supervised by Dr Alanna Rebelo and Prof Karen Esler.

Appendix 3. Publications

Cogill, L.S., Toucher, M., Wolski, P., Esler, K.J., & Rebelo, A. J. (2025). Evaluating the performance of satellite-derived evapotranspiration products across varying bioclimates in South Africa. *Under review with Remote Sensing Applications: Society and Environment.*

Skosana, T.E., Esler, K.J., & Rebelo, A.J. (2025). Exploring the trade-offs between spatial and spectral resolution in mapping invasive alien trees. *Under review with Remote Sensing Applications: Society and Environment.*

Rebelo, A.J. (2024). Mapping project sheds new light on alien invasion of SA catchments; Waterwheel: https://www.wrc.org.za/mdocs-posts/the-water-wheel-may-june-2024/

Rebelo, A.J., Esler, K.J., & Le Maitre, D.C. (2023). New project aims to map alien invasive trees. *The Water Wheel*. January/February Edition. https://www.wrc.org.za/wp-content/uploads/mdocs/WW%20Jan-Feb%202023%20web.pdf

Appendix 4. Supplementary material

Table S1. *List of indices used in the Sentinel-2 classifications.*

#	Index	Name in full	Equation	Reference
1	NDVI	Normalized Difference Vegetation Index	(NIR - Red) / (NIR + Red)	Tucker (1979)
2	Chlogreen	Chlorophyll Green Index	(Rededge4) / (Green + Rededge1)	Bolyn et al. (2018)
3	LAnthoC	Leaf Anthocyanid Content	Rededge3) / (Green + Rededge1)	
4	LCaroC	Leaf Carotenoid Content	(Rededge3) / (Blue - Rededge1)	
5	LChloC	Leaf Chlorophyll Content	(Rededge3) / (Rededge1)	
6	BAI	Built-up Area Index	(Blue - Rededge4)/(Blue + Rededge4)	
7	GI	Greenness Index	Green/Red	
8	gNDVI	Green Normalized Difference Vegetation Index	(Rededge4-Green)/(Rededge4+ Green)	
9	MSI	Moisture stress index	SWIR1/ Rededge4	
10	NDrededgeSWIR	Normalized Difference of Red Edge and SWIR2	(Rededge2 - SWIR2) / (Rededge2 + SWIR2)	
11	NDTI	Normalized Difference Tillage Index	(SWIR1 - SWIR2) / (SWIR1 + SWIR2)	
12	NDVIre	Red Edge Normalized Difference Vegetation Index	(Rededge4- Rededge1) / (Rededge4+ Rededge1)	
13	NDVI1	Normalized Difference Water Index 1	(Rededge4- SWIR1) / (Rededge4+ SWIR1)	
14	NDVI2	Normalized Difference Water Index 2	(Green - Rededge4) / (Green + Rededge4)	

15	NHI	Normalized Humidity Index	(SWIR1 - Green) / (SWIR1 + Green)	
16	EVI	Enhanced Vegetation Index 1	2.5 * ((NIR - Red) / (NIR + 6*Red-7.5*Blue)+1)	Jiang et al. (2008)
17	EVI2	Enhanced Vegetation Index 2	2.4 * ((NIR - Red) / (NIR + Red +1))	
18	EVI2_2	2-band Enhanced Vegetation Index	2.5 * ((NIR - Red) / (NIR + 2.4 * Red +1))	
19	MSAVI	Modified Soil Adjusted Vegetation Index	(2 * NIR + 1 - sqrt(pow((2 * NIR + 1), 2) - 8 * (NIR - Red))) / 2	Qi et al. (1994)
20	Norm-G	Normalized Green	(Green) / (NIR + Red + Green)	Bolyn et al. (2018)
21	Norm-NIR	Normalized Near Infra-Red	(NIR) / (NIR + Red + Green)	
22	Norm-R	Normalized Red	(Red) / (NIR + Red + Green)	
23	RededgePeakArea	Red Edge Peak Area	(Red + Rededge1 + Rededge2 + Rededge3 + Rededge4)	
24	RedSWIR1	Red – SWIR Bands Difference	(Red - SWIR)	
25	RTVIcore	Red Edge Triangular Vegetation Index	(100 * (Rededge4- Rededge1) - 10 * (Rededge4- Green))	
26	SAVI	Soil Adjusted Vegetation Index	((Rededge4- Red) / (Rededge4+ Red + 0.5) * 1.5)	
27	SR-BlueRededge1	Simple Blue and Red Edge 1 Ratio	(Blue / Rededge1)	
28	SR-BlueRededge2	Simple Blue and Red Edge 2 Ratio	(Blue / Rededge2)	
29	SR-BlueRededge3	Simple Blue and Red Edge 3 Ratio	(Blue/ Rededge3)	
30	SR- Rededge4Blue	Simple ratio Red Edge 4 and Blue	(Rededge4/ Blue)	

31	SR-Rededge4Green	Simple ratio Red Edge 4 and Green	(Rededge4/ Green)	
32	SR- Rededge4Red	Simple ratio Red Edge 4 and Red	(Rededge4/ Red)	
33	SR-Rededge4Rededge1	Simple Red Edge 4 and Red Edge 1 Ratio	(Rededge4/ Rededge1)	
34	SR-Rededge4Rededge2	Simple Red Edge 4 and Red Edge 2 Ratio	(Rededge4/ Rededge2)	
35	SR-Rededge4Rededge3	Simple Red Edge 4 and Red Edge 3 Ratio	(Rededge4/ Rededge3)	
36	STI	Soil Tillage Index	(SWIR1 / SWIR2)	
37	WBI	Water Body Index	(Blue - Red) / (Blue + Red)	
38	NDMI	Normalized Difference Moisture Index	(NIR-SWIR)/(NIR+SWIR)	Wang and Qu (2007)
39	NDBR (NBR)	Normalized Difference Burning Ratio	(NIR-MIR)/(NIR+MIR)	Escuin et al. (2008)

Table S2. *Accuracy assessment of classification results for each of the five classifications for each catchment in South Africa. The green highlighted rows indicate the best performing classifications, the results of which are presented in this progress report. SVM = spectral vector machine; S2 = Sentinel2; S1 = Sentinel 1; RF = Random Forest; GTB = Gradient Tree Boosting; IAP = invasive alien plant; ALOS = Advanced Land Observing Satellite.*

						Overall		IAP Accuracy		Intra IAP Accuracy	
#	**Catchment**	**Number**	**Name**	**n classes**	**n points**	**Accuracy**	**Kappa**	**Accuracy**	**Kappa**	**Accuracy**	**Kappa**
1	Luvuvhu	L1	SVM_S2	18	4870	0.79	0.78	0.92	0.74	0.91	0.72
2	Luvuvhu	L2	SVM_S2 + S1			0.79	0.78	0.93	0.75	0.91	0.73
3	Luvuvhu	L3	SVM_S2 + ALOS			0.84	0.83	0.92	0.75	0.91	0.73
4	Luvuvhu	L4	SVM_All			0.85	0.84	0.93	0.77	0.91	0.74
5	Luvuvhu	L5	RF			0.9	0.89	0.96	0.87	0.95	0.85
6	Luvuvhu	L6	GTB			0.91	0.91	0.97	0.89	0.96	0.87
7	Tugela	T1	SVM_S2	17	4967	0.88	0.87	0.94	0.85	0.92	0.82
8	Tugela	T2	SVM_S2 + S1			0.87	0.87	0.95	0.86	0.92	0.82
9	Tugela	T3	SVM_S2 + ALOS			0.95	0.95	0.98	0.94	0.96	0.92
10	Tugela	T4	SVM_All			0.91	0.9	0.96	0.9	0.93	0.85
11	Tugela	T5	RF			0.95	0.95	0.98	0.94	0.96	0.92
12	Tugela	T6	GTB			0.95	0.95	0.98	0.94	0.97	0.93
13	uMzimvubu	U1	SVM_S2	15	4811	0.78	0.76	0.96	0.91	0.91	0.82
14	uMzimvubu	U2	SVM_S2 + S1			0.81	0.79	0.96	0.91	0.91	0.82
15	uMzimvubu	U3	SVM_S2 + ALOS			0.77	0.75	0.97	0.93	0.89	0.8
16	uMzimvubu	U4	SVM_All			0.78	0.76	0.97	0.93	0.89	0.8
17	uMzimvubu	U5	RF			0.87	0.86	0.97	0.94	0.94	0.89

18	uMzimvubu	U6	GTB			0.88	0.87	0.98	0.96	0.95	0.91
19	Sabie-Croc	S1	SVM_S2	17	4467	0.77	0.75	0.91	0.77	0.89	0.73
20	Sabie-Croc	S2	SVM_S2 + S1			0.81	0.79	0.94	0.83	0.91	0.78
21	Sabie-Croc	S3	SVM_S2 + ALOS			0.82	0.81	0.93	0.81	0.91	0.81
22	Sabie-Croc	S4	SVM_All			0.88	0.87	0.96	0.88	0.94	0.87
23	Sabie-Croc	S5	RF			0.77	0.75	0.97	0.93	0.89	0.8
24	Sabie-Croc	S6	GTB			0.78	0.76	0.97	0.93	0.89	0.8