REHABILITATION OF GRASSLANDS AFTER ERADICATION OF ALIEN INVASIVE TREES “EMVA KWE DYWABUSI”

Anthony Palmer, Onalenna Gwate, Bukho Gusha, Lesley Gibson, Zahn Münch, Sukhmani Mantel, Chenai Murata, Chris de Wet, Thantaswa Zondani, Adam Perry

WATER RESEARCH COMMISSION

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Rehabilitation of grasslands after eradication of alien invasive trees

"Emva kwe dywabusi"

Report to the

WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

BACKGROUND

Invasive alien plants (IAPs) remain a serious threat to the water supply and to storage reservoirs throughout South Africa. IAPs are known to use a large quantity of water through evapotranspiration, and the clearing and control of IAPs has been a major activity of the Working for Water (WfW) programme. Successful clearing of these often aggressive woody trees and shrubs requires careful regeneration of effective indigenous vegetation cover after the physical clear-felling and removal of the IAPs. Application of effective post-clearing management regimes is required in order to improve the grass cover within catchments and this can ensure that there is controlled runoff and groundwater re-charge. South Africa's water catchment areas receive insufficient rainfall (Blignaut and De Wit 2004). In addition, limited options for the construction of new reservoirs and water schemes has stimulated the need to explore other options for increasing and conserving water supplies (Ashton and Seetal 2002) and improved demand management.

RATIONALE FOR THE STUDY

Clearing of the IAPs on their own is not sufficient motivation to proceed with the national WfW programme, and there needs to be consideration of the sustainability of the landscape when the activities of WfW are completed. In order to ensure sustainability of landscape processes for human benefit, it is essential to build stronger links between the control of undesirable woody plants and the derived benefits to humans occupying the catchment. In order to strengthen this linkage, empirical evidence of the water use of every component of the landscape needs to be collected. The landscape units or land cover types that are encountered in the mesic regions of South Africa are diverse, comprising inter alia areas of irrigation agriculture, dryland cultivation, residential, extensive rangeland and forests. Superimposed on this are two different land tenure systems (land use), namely freehold farms with a long history of commercial agriculture, and communal or leasehold areas, with diametrically opposing approaches to landscape management. There is a need to improve our understanding of how to balance water use and carbon capture between different land cover types and land tenure systems as both these cycles are important to people and their livelihoods. Two possible approaches for assessing the relative efficiency of the landscape for secondary production are livestock water productivity (LWP) or water use productivity (WUP). In the rural landscapes of the south eastern parts of South Africa (e.g. former Ciskei, Transkei and Kwa-Zulu Natal), land-use is dominated by a complex arrangement of dwellings, livestock grazing, dryland cultivation and forestation, all within a communal land tenure system. Note that communal land is not privately owned, as commercial land is, but is held at a community level, usually in terms of some form of official customary (i.e. communally and 'traditionally' oriented) land tenure system. Land may be distributed under the allocatory authority of a leadership structure, whether of a more 'traditional' (i.e. chief/headman) type, or more recently, of a type consisting of a complex combination of 'traditional' and elective political elements. This is a socio-ecological system (SES) that is encountered throughout sub-Saharan Africa. Each component of the system is dependent on resources provided from the carbon capture process. For example, dwellings are often built using wood from the indigenous and invasive alien forests; livestock depend on the net primary production (NPP) from grasslands; annual crops provide food for the households; and forests provide wood fuel. The capture of carbon by the landscape is the primary driver of livestock and food production in this human-dominated SES and an understanding of the total economic value and water use efficiency (WUE) of these processes requires an empirical assessment of the water cycle. The rates of carbon accumulation are driven by the WUE of the full range of plants within this SES. When trying to define the optimum land cover options for this SES, it is necessary to understand fully the water used by each component of the landscape, and to integrate this understanding into a single unifying concept such as LWP or WUP. To date this has been difficult with micro-scale gauging experiments, however with the recent successful use of Earth observation data to prepare global models of evapotranspiration and NPP, it has now become possible to better quantify the water use and carbon gain of these diverse land cover types.

Limited options for the construction of new storage reservoirs and other water schemes have stimulated the need to explore other options for increasing and conserving water supplies. In addition, improved supply is a crucial option in the long-term planning of water provision for rural areas. Currently the major users of water and carbon in the project SES are livestock and alien trees, besides humans. By changing the landscape scale plant water use of either of these cover classes, supply to dams and rivers can be modified to suit end-user requirements. Rangeland management approaches have been introduced to reduce rangeland degradation and improve grassland production; however, these have not always been successfully applied in these rural SESs. As the land tenure system is based on communal ownership, some livestock owners may over-exploit the rangeland because access is poorly regulated and graziers are not encouraged or mandated to implement resource conservation measures. Similarly, benefit derived from improved cultivation and cropping techniques (e.g. conservation agriculture) are not directly translated to the advantage of the individual land-user. In developing scenarios that can convince land-users to change their behaviour and landuse patterns, it is essential to have an empirical understanding of the water use of each component of the ecosystem. This cam enable planners to evaluate the consequences of particular practices on the water balance. In this context, the overall project aim was to assess, and make recommendations for improving, the grass production from areas that have been cleared of wattle by the WfW.

PROJECT RESULTS

Livestock production domains

In the mixed farming system that was studied, livestock production is a key attribute of household food and livelihood security. By identifying the various production domains, and assessing their relative contribution to grass production, we are now able to recommend where appropriate interventions should be applied to achieve enhanced livestock production. For example, in the abandoned cultivated lands, there should be an active programme to avoid further invasion by black and silver wattle. In this domain, there should also be an active policy to assist with soil remediation (e.g. increasing the pH by addition of agricultural lime), and the planting of appropriate fodder grasses that will enhance livestock production during the dry season. In addition, the introduction of effective herding in the use of the un-improved grasslands, where livestock are taken to new, un-utilized areas on a daily basis, will enhance livestock performance. This, when combined with improved market access, will greatly enhance the household income from both sheep and cattle, which are the main livestock-based livelihood strategies. There have already been several initiatives within the project to enable livestock owners to participate in the developing value-chain market for natural beef products, and these should now be further encouraged.

Water use determination

This study used a Penman-Monteith-Palmer (PMP) equation to calculate ETa, which uses maximum LAI and potential ET to calculate actual ET. Similar to Palmer et al. (2017), maximum LAI of 3.84 was reported for unimproved grasslands. Maximum LAI for other domains were 4.1 in cultivated lands and 2.9 in areas around the homesteads. On unimproved grassland, PMP ETa of 270 mm was estimated for the year 2016, while MODIS ET for the year 2016 was 378 mm. This latter figure was used for all calculations of LWP as PMP has underestimated ET for sub-humid grasslands.

Rangeland productivity

Improving rangeland productivity through grazing management is one possible way of improving livestock water productivity. An adaptive stocking density and appropriate herd composition may positively influence vegetation ground cover, species composition and net primary productivity, and thus improve water use. In this study, we described the biophysical attributes of the ecosystem in a communal rangeland where everyone has equal access and conventional grazing management is poorly implemented. This study supports an estimated annual ET for 2016 over the unimproved grasslands of 378 mm in 2016 (MOD15), which will be used in all further analysis of LWP. Canopy cover was found to be a good predictor of above-ground dry grass biomass production in heavily grazed ecosystems. The ANPP was comparable to other studies conducted across South Africa and shows that rangeland production does not depend on the tenure system as communal rangelands were as productive. This implies that many factors exist that determine the annual herbage production other than grazing.

Annual grazing capacity maps were generated for T35B and S50E catchments using Landsat 8 and MODIS. The results found that productivity (Gross Primary Productivity [GPP], NPP and grazing capacity) derived from Landsat 8 were consistently underestimated due to partial accumulation over a year and influence of low quality images, e.g. cloud cover. A user interface for land use productivity has been designed, but additional work is required with in-field testing to improve the accuracy of the results. This approach is expected to provide non-expert users with a means of estimating in-field land use productivity for grasslands.

Soil characteristics after wattle clearing and a trial of a rehabilitation possibility

The soil analyses found that the invasion status had statistically significant effects on P, K, N, Cation Exchange Capacity (CEC), total cations, acid saturation and pH ($p < 0.05$), whereas marginal significant differences were detected for Mg and Zn ($p < 0.1$). Since soil characteristics are crucial in managing grasslands (they are the substrate for forage production) a clearing and control liming experiment, that was followed over six months of the growing season, was conducted on an IAP invaded farm. The results demonstrated an increase in P in the soils samples by treatment level and a dramatic increase in LAI and biomass from beginning of trial, although difference between treatments could not be detected because of the high spatial variability. Additionally, the highest categories of lime treatment supported more prostrate broadleaf grass species over upright species in terms of area covered, and these treatments also had higher Normalised Difference Vegetation Index (NDVI) values.

Ecosystem services related research

The importance of lay/local knowledge systems in ecosystem management in the contemporary age cannot be overemphasised. Lay/local knowledge systems often find it difficult to respond to slow ecological processes such as soil erosion, vegetation changes and climate change. Moreover, largely because of its heavy reliance on personal experience, lay/local knowledge might find it difficult to comprehend more indirect services such as Regulatory and Supporting ES.

A mapping exercise with the communities helped identify areas that the residents are interested in developing for various purposes. Aerial maps were effective in understanding the dynamics of the area, and in generating discussion about future ideas of intervention and rehabilitation. We also introduced a number of business opportunities to the community for managing land and livestock marketing including selling timber to a company (PG Bison) and organising livestock sales following the Meat Naturally model. A number of alternative management strategies such as thinning (instead of clear-felling) are discussed in the report.

Finally, a multi-criteria decision analysis (MCDA) was conducted for prioritising clearing operations in Tsitsa River catchment with input from decision-making stakeholders and other researchers working in the catchment. The plan needs to be updated with additional data and will be delivered to DEA and WfW working in the area through the team's continued post-project interaction with the Tsitsa Project that is run through Rhodes University.

PROJECT CONCLUSIONS

The conclusions from this project are broadly summarised under four broad main headings that relate to water resources and catchment management.

Ecosystem services as an over-arching framework

Using appropriate epistemologies, this project brought together scientific and social knowledge on rehabilitating grasslands after removal of invasive aliens. The following recommendations are derived from our research that have implications for future research, and work conducted by WfW and DEA projects in the catchment:

- In order for a RES framework to operate effectively, there needs to be a strong relationship between the resource and the products / services produced.
- In contrast to provisioning and cultural services, the regulatory and supporting services were not well understood by the communities. Thus, researchers and practitioners need to consider means and opportunities to improve the capacity of local people to respond to signals from the natural environment that are not immediately obvious or have direct impacts on the community, such as carbon sequestration, climate regulation, waste decomposition and detoxification.
- From both a research and a policy perspective, it is important to acknowledge the mutual complementarity of both more universal, scientifically-derived knowledge and more locally situated knowledge and values in ecological services related undertakings, including water services decision making. It is important that policies continue to be developed for

the devolution of water resource management to local level groupings. Thus, policy and decision-makers should consider implementing actions and policies that contribute towards Reward for Ecosystem Services practices at local level.

Water resource protection

The community engagement aspect of our project found that the two primary concerns that the local people aspire to see improved in their natural environment are water sources and grasslands. Communities indicated an interest in grazing camps that can be used over winter and summer in order to prevent overgrazing, and to provide quality forage during the dry season. There was also support for improving the current soil condition, grass species composition and production, as well as the planting of appropriate forage pasture grasses. There was also interest in changing the current wattle management strategy of clear-felling to one of selective thinning. These are all leveraging points for future interaction with, and involvement of the communities in managing their land and water resources, and adapting the policy of the Extended Public Works Programme.

Improving rangeland productivity through grazing management is one possible way of improving LWP. An adaptive stocking density and appropriate herd composition strategy may positively influence vegetation ground cover, species composition and NPP, and thus improve water use. The results of our study showed that rangeland production does not depend on the tenure system as communal rangelands were as productive as commercial ones. This implies that many factors exist that determine the annual herbage production other than grazing. Therefore, there is a need for proper grazing management plans to be put in place to prevent excess water loss on communal rangelands. The disc pasture meter is a useful management tool which could be used by poor resource farmers to enable them to determine where to graze and rest their rangelands.

Household food and water security

The link between good catchment and landscape management and household food security is very tenuous as there is seldom a clear link between compliance by a household and 'return for effort', or obvious advantages accrued by complying with landscape management recommendations. It is most often the poorer households that suffer as a result of non-compliance by other, better-resourced villagers. There are several explanations for this fractured relationship. The voices of individuals that are poorly resourced and those with less power in the decision-making process need to be brought to the fore in research projects whenever possible.

In the mixed farming system that we studied, livestock production is a key attribute of household food and livelihood security. By identifying the various production domains, and assessing their relative contribution to grass production, we are now able to recommend where appropriate interventions should be applied to achieve enhanced livestock production including avoiding further invasion of abandoned cultivated lands, assisting with soil remediation (e.g. increasing the pH by addition of agricultural lime), and the planting of appropriate fodder grasses that will enhance livestock production during the dry season. In addition, the introduction of effective herding combined with improved market access, will greatly enhance the household income from both sheep and cattle, which are the main livestock-based livelihood strategies. There have already been several initiatives within the project to enable livestock owners to participate in the developing value-chain market for natural beef products

Catchment governance

The aerial maps used during the first workshop were effective in understanding the dynamics of the area, and in generating discussion about ideas on intervention and rehabilitation. We recommend use of these maps in future interaction with communities to allow them to gain better understanding of their resources and for discussing ways for managing these resources cooperatively.

We recommend that rehabilitation by agencies external to the communities ought to be conceived in terms of some of the social concerns facing communities instead of simply for improving soils or planting grasses. Wattle is an important resource in some areas e.g. for fencing, house construction, and as a fuel source. Protecting and improving grazing seemed to be the most important aspect of rehabilitating lands after the removal of wattle.

The results of this study revealed huge variations in selected soil abiotic factors across environmental gradient in response to the invasion of *A. mearnsii*. Both the site and interactive effects of site and invasion status contributed significantly to variations in soil variables. Hence, any rangeland management intervention in complex social-ecological systems (SES) should be informed by an appreciation of local soil physico-chemical properties. The clearing and liming trial experiment showed that grasses can return in significant biomass when grazing is excluded for as short a period as six months. This supports the idea of resting being an important part of grassland management.

RECOMMENDATIONS

There are potential commercial partnerships which need to be embraced and supported given that there are strong connections already taking place with PG Bison for some villages.

Communities also indicated interest in removing wattle and having pine as a communal resource for homestead use in construction, as well as a revenue generation stream through sale to PG Bison. We therefore, suggest future research to investigate how these connections can be forged between the communities and industry.

Future research needs to interrogate means and opportunities to improve the capacity of local people to understand the importance of regulatory and supporting services. For this, investigating implementation of a RES programme at local level to promote coherent and sustainable catchment management by the communities is suggested.

Participatory and community-enabling research methodologies developed at the local level can enable local people to comprehend and negotiate the central issues relating to their natural environment and to ecosystem services more effectively, and to deal with policy makers in this regard. This calls for long-term engagement with local communities and funding agencies need to consider implications for project sustainability.

Relationships with the commercial beef and wool industries need to be further developed and cultivated. The wool marketing frameworks have already been established. However, there was less evidence of successful beef marketing options, and the project encouraged the cattle farmers to organise regular auctions and to consider joining an existing consortium.

FUTURE RESEARCH

- Investigate how connections can be improved between the communities and industries that are active in the region, including commercial timber and chip board production, as well as wool and beef production.
- Investigate further the implementation of a RES programme at local level to promote coherent and sustainable catchment management by the communities.
- Investigate further the role of herders in improving household level livestock production efficiencies. A targeted study that intervenes by providing herders to pre-selected with the view to quantifying improvements in household production efficiency.

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LIST OF ABBREVIATIONS

ACIAR	Australian Centre for International Agricultural Research
AET	Actual Evapotranspiration
AGB	Above-ground biomass
ANPP	Above-ground Net Primary Productivity
ARC	Agricultural Research Council
AT	Albany Thicket
AWS	Automatic weather station
BRS	Bare rock and soil (natural)
CEC	Cation Exchange Capacity
CLs	Cultivated lands
CSA	Conservation South Africa
CSES	Complex Social-Ecological Systems
DBH	Diameter at breast height
DEA	Department of Environmental Affairs
DoY	Day of Year
DPM	Disk pasture meter
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
EBR	Energy balance closure ratio
EC	Eddy covariance system
EGR	eZulu Game Reserve
ERS	Environmental and Rural Solutions
ES	Ecosystem services
ET	Evapotranspiration
ET	Evapotranspiration
ET0	Reference / Potential Evapotranspiration
ETa	Actual evapotranspiration
FITBs	Forest indigenous, thicket bushlands, bush clumps, high fynbos
FP	F Forest plantations (clear-felled, pine spp., other/mixed spp.)
fPAR	Fraction of absorbed photosynthetically active radiation
GEE	Google Earth Engine
GIS	Geographical Information Systems
GPP	Gross primary productivity
IAP	Invasive alien plant

IWRM	Integrated Water Resources Management
LAI	Leaf area index
LAS	Large aperture scintillometer
LC	Land cover
LCC	Land cover change
LCCS	Land cover classification systems
LCM	Land Change Modeller
LE	Latent heat flux
LULCC	Land use land cover change
LWP	Livestock Water Productivity
MAE	Mean Absolute Error
MAR	Mean Annual Rainfall (mm)
MCDA	Multi-criteria decision analysis
MDTP	Maloti Drakensberg Transfrontier Programme
MDV	Mean Diurnal Variations
MNP	Meat Naturally Pty
MODIS	MODerate Resolution Imaging Spectroradiometer
NDVI	Normalised Difference Vegetation Index
NEE	Net ecosystem exchange
NLC	National Land Cover
NPP	Net primary production
NRM	Natural resource management
PBIAS	Percent bias
PCA	Principal Component Analysis
PCQ	Point-Centred Quarter
PES	Payment for ecosystem services
PET	Potential evapotranspiration
PF	FITBs persistence
PM	Penman-Monteith
PML	Penman-Monteith-Leuning
PMP	Penman-Monteith-Palmer
PsnNet	Net photosynthesis
QA	Quality Assessment
QC	Quaternary Catchment
REALU	Reducing emissions from all land uses
RES	Rewards for ecosystem services

RMSE	Root mean square error
RSR	Root mean square error observations standard deviation ratio
SEBAL	Surface Energy Balance Algorithm for Land
SEBS	Surface Energy Balance System
SES	Social-Ecological System
SWC	Soil water content
TAMSAT	Tropical Applications of Meteorology Using Satellite Data and Ground-Based Observations
TD	Transdisciplinarity
TLU	Tropical Livestock Unit
UG	Unimproved grassland
UrBu	Urban/built-up (residential, formal township)
VBP	Value Beef Partnership project
VPD	Vapour pressure deficit
Wb	Water bodies
WfF	Working for Fire
WfW	Working for Water
Wl	Wetlands
WP	Water productivity
WRM	Water resources management
WUE	Water Use Efficiency
WUP	Water Use Productivity
ZAR	South African Rand

Symbols

D_a	Water vapour pressure deficit of the air (kPa)
$E_{eq,s}$	Equilibrium soil evaporation (mm)
E_s	Soil evaporation (mm)
G_a	Aerodynamic conductance to water vapour (m s^{-1})
G_c	Canopy conductance (m s^{-1})
R_n	Net radiation (W m^{-2})
e_a	Actual vapour pressure deficit (Pa)
e_a	Saturation vapour pressure (Pa)
f_{SWC}	Fraction of soil evaporation using volumetric water content
f_{drying}	Fraction of soil evaporation using the rate of soil drying after precipitation

f_{zhang}	Fraction of soil evaporation using precipitation and equilibrium evaporation ratio
g_s	Stomatal conductance
g_{sx}	Maximum stomatal conductance (m s^{-1})
Δ	Slope (s) of the curve relating saturation water vapour pressure to temperature (kPa^{o}C^{-1})
LAI_{max}	Maximum leaf area index
G	Soil heat flux (W m^{-2})
P	Precipitation (mm)
T	Transpiration (mm)
α	Parameter controlling the rate of soil drying (day^{-1})
ε	Slope (s) of the curve relating saturation water vapour pressure to temperature
F	Function to be minimised
R_n	Net radiation (Wm^{-2})
f	Fraction of evaporation from the soil (0 – 1)
u	Wind speed (m s^{-1})
λE/ LE	Latent heat flux (W m^{-2})

CHAPTER 1 INTRODUCTION AND OBJECTIVES

by

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1.1 Background

IAPs remain a serious threat to the water supply to storage reservoirs throughout South Africa. IAPs are known to use a large quantity of water through evapotranspiration, and the clearing and control of IAPs has been a major activity of the WfW programme. Successful clearing of these often aggressive woody trees and shrubs requires careful regeneration of effective indigenous vegetation cover after the physical clear-felling and removal of the IAPs. Application of effective post-clearing management regimes is required in order to improve the grass cover within catchments and this can ensure that there is controlled runoff and groundwater re-charge. Earlier, water demands were met through a complex system of engineering supply side solutions which included costly reservoirs, inter-basin transfer and water pumping schemes (Smakhtin et al. 2001). South Africa's water catchment areas receive insufficient rainfall (Blignaut and De Wit 2004) to support the growing demand for agricultural, industrial and human consumption. Limited options for reservoirs and schemes has stimulated the need to explore other options for increasing and conserving water supplies (Ashton and Seetal 2002) and improved demand management. Therefore, through an improved understanding of the water use of rural landscapes dominated by mixed farming systems, one of the aims of this project has been to develop and implement cost-effective, robust methods for determining ETa. As there is a direct link between ETa and gross primary production, these methods could also be used to improve livestock production estimates, and to assess the local appetite for a PES scheme in which livestock owners can be encouraged to improve the vegetative cover in the catchments they manage and receive direct compensation from the water user (e.g. dam owners, local authorities, irrigation agriculture) (Engel et al. 2008). Further, the project aimed to assess the interventions necessary to optimise the post-clearing rehabilitation initiatives of the WfW programme.

1.2 Project aims

The overall project aim was to assess, and make recommendations for improving, the grass production from areas that have been cleared of wattle by the WfW. The specific aims were:

Aim 1. To parameterize, evaluate and modify suitable models for evapotranspiration (ET), LWP and NPP estimates for IAPs and grasslands.

Aim 2. To explore and compare ET, LWP and NPP in three catchments with contrasting land tenure systems, comprising diverse biomass and condition states for grassland and IAPs.

Aim 3. To apply the selected models for predicting ET, LWP and NPP to these catchments.

Aim 4. To examine the possibility of using a RES system in rural rangelands as a possible solution to degradation and water issues (quantity and quality).

1.3 Epistemologies

There are many formalised ways of understanding and knowing about reality that are consistent with complex systems ontology. We have selected a core set that have been used internationally to advance the understandings of people in relation to the bio-physical world (for example, the Integrated Water Resources Management [IWRM] approach that emphasises integration). We have integrated scientific methodological approaches with how local people conceptualise the world and especially the bio-physical world during the research. In the course of this project, other epistemologies were also used.

1.3.1 Complex social-ecological systems (CSES)

Having accepted that the nature of the world is systemic complexity, it is logical to understand humans – and societies – embedded in the bio-physical world as part of a CSES (Figure 1.1) (Biggs and Rogers 2003; Folke et al. 2004). Consequently, it is necessary to take explicit account of the characteristics of complex systems when engaging with water resource issues.

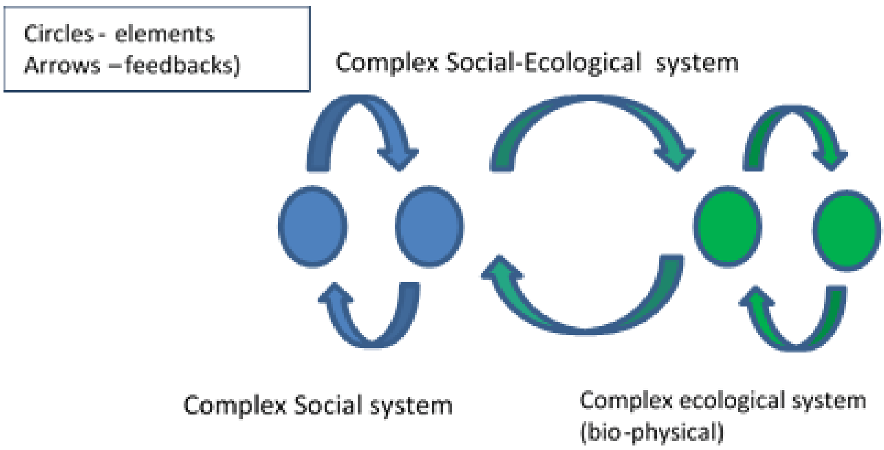

Figure 1.1 A diagram illustrating that complex CSESs include interactions and feedbacks between the elements of complex social systems and complex ecological systems. (Adapted from a presentation by R. Biggs, Stellenbosch, 2016)

At present, water resources management (WRM) largely relies on strong assumptions of linearity and direct causal relationships. Evidence-based management mainly relies on the use of traditional reductionist scientific approaches. Even much modelling (which may well be complicated) does not include elements of complexity. This response to understanding the world has served us reasonably well, as there are circumstances when failing to acknowledge complexity does not appear to matter much (consequences are often externalised to environmental costs which may take some time to become evident). There are also many examples of linear causal relationships within complex systems. But we are approaching thresholds of water availability and quality, and the powerful influence of society, both in causing degradation and in experiencing shortage (e.g. public protests at lack of service delivery) is impacting on WRM processes. It is time to face the challenge posed by the inherent characteristics of complexity when dealing with water and "people on the planet" (Rogers et al. 2013).

1.3.2 Transdisciplinarity (TD)

Nicolescu (2000) discusses the inevitable link between complexity and TD, and Swilling and Annecke (2012) place this connection in the specifically South African context of linked social and ecological justice, where knowledge is power, exercised in a context where natural resources, and the benefits of natural resources, are unequally distributed and accessed.

When Integrated Water Resources Management (IWRM) practice is viewed in the context of CSESs, it becomes obvious that a wide range of skills and knowledge sources are needed: multi-, inter- and particularly transdisciplinary teams and processes. When working in CSESs, it is especially important to acknowledge that knowledge resides in all people involved and that the co-creation of new knowledge and knowledge exchange are more powerful approaches than knowledge transfer (for example, Rogers et al. 2013). TD is particularly appropriate in respect of Adaptive IWRM. Firstly, it is explicitly "problem focused", so creative energy is applied to solutions, resolutions and the loosening of "wicked" (Rittel and Webber 1973) problems. Wicked problems arise directly from the nature of complex systems because not all the consequences of particular responses and actions can be envisaged, so whenever action is taken, unintended consequences arise, sometimes of alarming proportions.

The metaphor we have come to use is that of the "knot" – which refers also to the notion of “tangledness” in the Principles for Adaptive IWRM. When one tries to untangle a piece of fishing line picked up on the beach, tugging in one place often tightens another, and then there is the seaweed, or fishing hooks that have become entangled. At first a lot of energy goes into loosening the knot. In Adaptive IWRM the best we can often aspire to, is the conscious recognition of new options that arise as "knotty" problem areas are loosened, mindful of the future knots that will necessarily emerge. However, the team work, confidence and ability to take action, to monitor consequences and adjust direction become empowering ways of operating.

Max-Neef (2005) uses a TD understanding to organise discipline-based ways of knowing into a hierarchy, where the foundation layer provides the capacity to address an empirical domain, and to describe what exists, the "what is" of the system (using for example physics, mathematics, ecology, geology, politics, economics). This supports the capacity for pragmatic action, framing the next level - what we are capable of doing (e.g. policy, risk analysis, engineering, agriculture, industry, commerce). This in turn supports normative considerations of what we want to do using, for example, adaptive management, planning, scenario development, design, politics, and law. Finally, the practices that overarch (and underpin) everything else, guiding how, why, and if, we do what we want to do, use values, ethics and philosophy. In the context of the South Africa, the early democracy water law reform process was based on an acknowledgement of values, and of the fundamental importance of a principled, and ethical basis for drafting of policy, law and practice (Asmal and Hadland 2011). There is much to learn from reflecting on that process. We use the Max-Neef layers to structure each of the case studies (Figure 1.2).

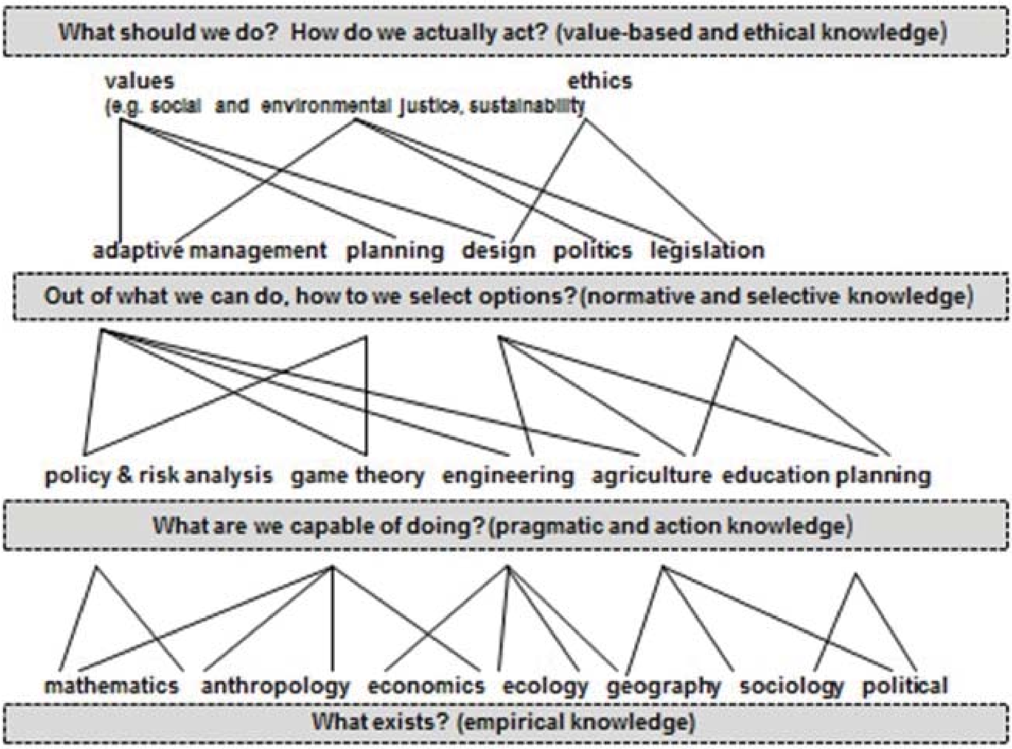

Figure 1.2 A diagram adapted from the layered concept of transdisciplinarity Max-Neef (2005)

We draw on two aligned definitions of TD:

“Transdisciplinarity is a reflexive, integrative, method-driven scientific principle aiming at the solution or transition of societal problems and concurrently of related scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge.” (Lang et al. 2012)

“Transdisciplinary is a reflexive research approach that addresses societal problems by means of interdisciplinary collaboration as well as the collaboration between research and extra-scientific actors; its aim is to enable mutual learning processes between science and society; integration is the main cognitive challenge of the research process.” (Jahn 2012)

Adaptive IWRM therefore seeks to build, and learn to benefit from well- functioning TD research and practice teams, deliberately exploring boundary areas currently separated into silos (for example WRM and water service delivery or water quantity and quality).

1.3.3 Resilience

Resilience thinking and practice (Folke 2006; Pollard et al. 2008) provides a conceptual framework and guides for application (Resilience Alliance 2010) that are founded on the recognition of feedbacks (Figure 1.3). Resilience is a system characteristic observed as the capacity of a system to experience stresses, to change, and yet to retain key structure, function and process identity. Where these recognisable features change there is deemed to have been a change of state. The process of large magnitude change is understood as a transition past a threshold (Walker and Noy-Meir 2001). Increasingly the ecological parts of a CSES are seen as providing their related societies with valued goods and services. When use of the ecosystem threatens to move ecological processes through thresholds into a new state which perhaps offers fewer services, it seems important to recognise approaching thresholds and adapt. In Adaptive IWRM this means paying attention to water use stressors such as abstraction and waste disposal.

The recognition of resilience traps, thresholds and changes of state are critical in the practical unfolding of this project. For example, degradation is itself a “change of state” phenomenon, as is the shift from a productive to a less productive grassland. Poverty is a resilience trap that drives water and livelihood issues arising from degradation. Fabinyi et al. (2014) refer to “rigidity traps” as being especially characteristic of the social aspects of a CSES. Rigidity traps resist transformation (in a positive direction), so, while transformation may be necessary, it is resisted through current power structures. This provides a social interpretation of the conservation phase and its rigidity.

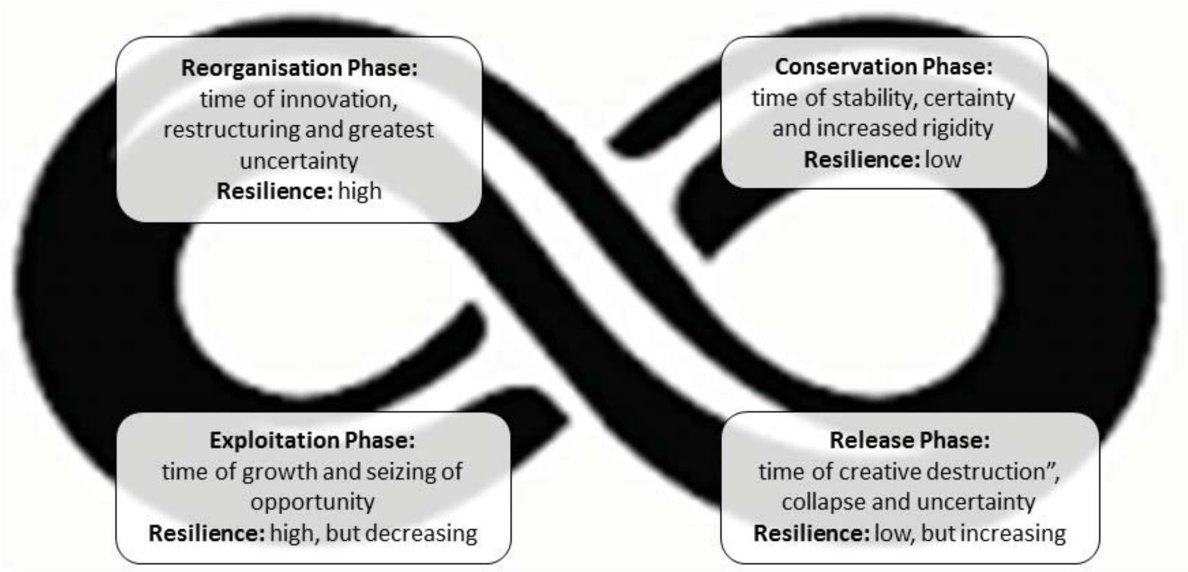

Figure 1.3 Resilience: a generalised diagram of the cycle of regenerating change (Walker et al. 2004). Such cycles can be linked and nested at different scales (Gunderson and Holling 2002), and each phase is characterised by thresholds of change. (Note the infinity symbol, lemniscate, is used).

Processes of change also occur at different spatial and temporal scales. As we seek to ***act*** in ways aligned with Adaptive IWRM thinking, it is useful to recognise that uptake of new ideas and practices depend on the context and circumstances. Becoming alert to sensing contextual change alerts practitioners to "widows of opportunity" (Figure 1.4).

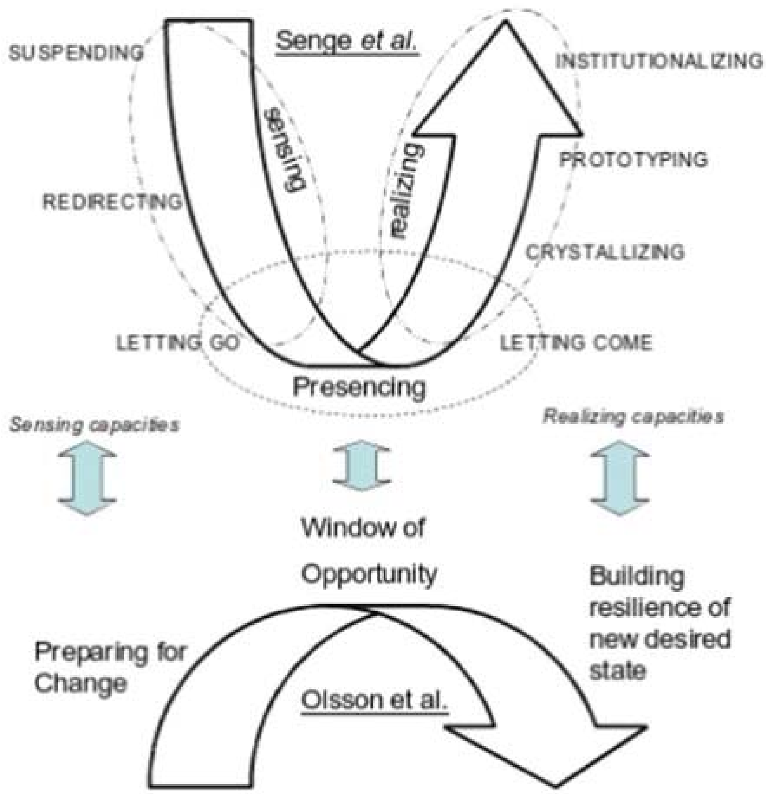

Figure 1.4 Resilience may be conferred by the capacity to recognise and take advantage of a "window of opportunity". Source: Biggs et al. (2008), and drawing on Olsson et al. (2004).

Adaptive IWRM pays attention to the resilience of CSESs; using monitoring to identify trajectories of change towards thresholds and potential changes of state in systems; and seeks to expand learning about how to respond to recognised thresholds.

1.3.4 Social learning

Building on complexity, CSESs, trans-disciplinarity and resilience, leads directly to social learning, which, in CSESs, is strongly associated with stakeholder participation (Pahl-Wostl et al. 2007; Ison 2008; Ison et al. 2007) and is defined as having taken place by Reed et al. (2010) if: (1) there is a change in understanding of learners; (2) this change is shared and understood within a broad social context or community of practice and (3) the learning has taken place through social interaction. In terms of symbols, there is a clear parallel in resilience and social learning in the symbolic use of a lemniscate, or the infinity symbol (Figure 1.5) (Wals et al. 2009). The symbol provides a rich image of a continual process of input and feedback driven change, within an infinite system. A process of alertness to current situations, response to change, and learning from actions is necessary. Learning relies on reflection on situations, actions and responses – and attentiveness to wide range sources (Figure 1.5).

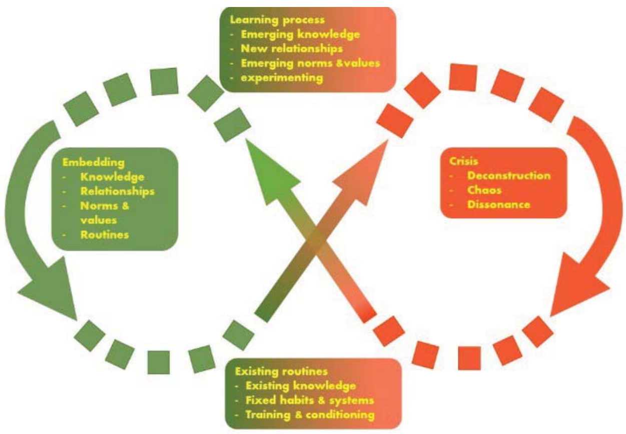

Figure 1.5 A social learning system (Wals et al. 2009, based on Hurst 1995). (Note: infinity symbol, a lemniscate, used again, as in the resilience diagram Figure 1.3)

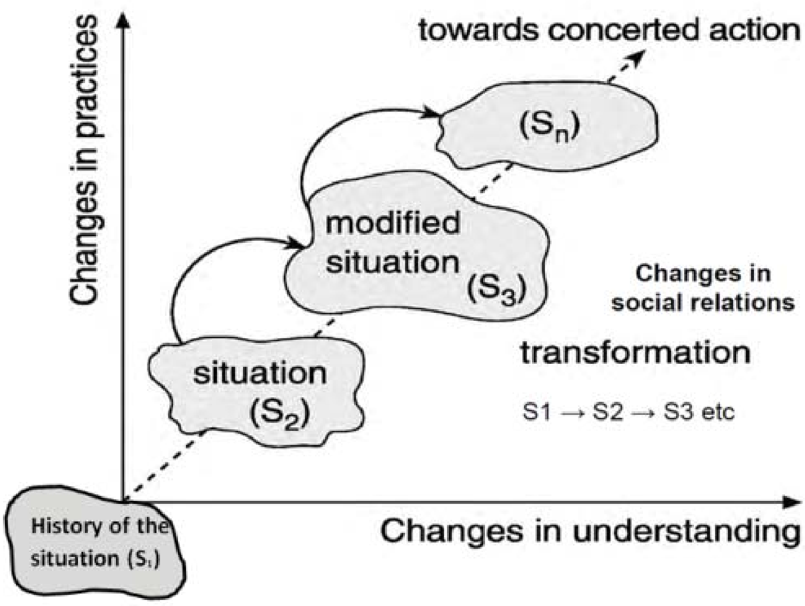

Figure 1.6 A diagram adapted from Ison (2010) illustrating how the start of a project system has a history, and that transformational change as the system progresses through time can be tracked by noting and analysing changes in practice (doing) concurrently with changes in understanding. Both the doing and the understanding drive each other along a trajectory of learning and concerted action.

Acting in ways aligned with Adaptive IWRM will therefore include reflection within the research team, and among the emerging community of practice that will arise in the case study locations. Adaptive IWRM will become a responsive learning arena.

1.3.5 Political ecology

The V-STEEP analysis (values, social, technical, ecological, and political; Rogers et al. 2013), which is used to take account of any context in terms of the influence of values and social, technical, environmental, economic and political factors, is a key step in Strategic Adaptive Management (SAM). IWRM has long been the domain of engineers, more recently of ecologists and latterly social scientists and economists have come into play. Increasingly we must take account of politics. In this research, we have used political ecology (Greenberg and Park 1994) because political ecology places an understanding of a biophysical reality – with all its complexity – into a political reality (a particular perspective on a complex social system). Political ecology allows a discursive analysis of particular issues, for example water (Johnston 2003), within a political discourse. Applications of political ecology to IWRM have come from Chile (Budds 2004) and Mexico (Delgado-Ramos 2015). In South Africa, Hallowes and Munnik (2016) present a trenchant view of the coal mining political ecology, with its water connectivity.

Political ecology provides a useful Adaptive IWRM approach within IWRM, particularly in the V-STEEP analysis within SAM. Political ecology is particularly useful for practitioners coming from disciplines unused to taking account of politics.

As the social side of CSES's comes more firmly under the spotlight, new challenges open up. Fabinyi et al. (2014) recognise 1) there is more diversity within groupings such as communities, or even institutions than previously acknowledged, leading to added complexity; 2) power issues are important and 3) CSES thinking needs to probe the consequences of its focus on biophysical, because stakeholders' interest may not be focused on the biophysical, but rather on broader political issues.

1.3.6 Science and citizen science

There is no doubt that natural science remains important to natural resource management and Adaptive IWRM. However, how science is done comes into question in Adaptive IWRM. To make informed decisions, stakeholders need to find ways of participating in science (Graham 2012; Graham et al. 2015; Graham et al. 2016). This may include understanding how science works, how scientific agendas are set, and practicing science as citizen's science. Science becomes both more controversial and more relevant in this paradigm.

Collectively, this thinking could be called "post normal science" (Gallopin et al. 2001) and emerges from the recognition that conventional science which has served, and continues to serve humanity so well, has real limitations. The world as we know it includes phenomena that are not amenable to reductionist, deductive approaches, top-down linear management, or easily known cause and effect relationships.

1.4 The Adaptive IWRM project framing

Key adaptions in this research project

Five major synergies were made during this research project:

1. Selection of villages – Recognition of different land tenure arrangements and land tenure history. Recent communal versus old communal, and freehold land with a long history of commercial agriculture.
2. Integrating water and livestock – Free-Range Beef Product which is a value-chain product driven largely by the premium beef market and the Woolworths Supermarket Chain. Collaborating institutions include Agricultural Research Council (ARC), Cradock Abattoir, Cavalier Meats, and Australian Centre for International Agricultural Research (ACIAR). An alternative market option was also presented - Meat Naturally.
3. Tsitsa Project – New research partners emerged and were profoundly influenced by the adaptive perspective: The Department of Environmental Affairs (DEA) in collaboration with DWS, initiated a project to restore ecological infrastructure and support rural livelihoods in the Tsitsa River catchment, upstream of the proposed Ntabelanga and Laleni Dams (Fabricius et al. 2016). **The project team recognised the DEA was undertaking a very large project that would benefit from Adaptive IWRM thinking and practice.** Resources were used to interact regularly with DEA management and operations: (i) Senior management (Director General, Deputy Director General, Chief Directorate, Directorate); (ii) provincial management; (iii) provincial operations; and (iv) implementing agents. Through this, the Chief Directorate for Natural Resource Management (DEA: NRM) has formally adopted several of the recommendations from this project. We believe that with more direct interactions, the results from the evapotranspiration modelling can be integrated into the stream flow reduction licensing processes of the DWS.
4. National Equipment Programme's support for the purchase of a LAS – The project team, in collaboration with Rhodes University and the ARC-Animal Production, acquired and installed high precision equipment to assess actual evapotranspiration across two land cover classes.
5. CGU and Edinburgh University – The team maintained an international component through links with CGU and Edinburgh University in Scotland.

1.5 Data gathering and data analysis

The (a) data gathering, and (b) related data analysis methods used were:

1. a) Critical literature review, paying particular attention to the interface between disciplines and knowledges; b) Critical analysis.
2. Adaptive field techniques that provide data on water use, soil chemistry, biomass production, land use, livestock production.
3. a) Case study selection and b) mixed methods analysis (see below 5 to 7).
4. a) Identification of the (i) elements, and (ii) the relationship between elements of the relevant CSES, paying particular attention to feedbacks, scale, context, and non-linearity. b) Systemic analysis.
5. a) Quantitative data gathering: the conventional scientific method was used, with considered, replicated, quantitative measuring and data gathering. This method was applied in all the biophysical aspects of the project, and for quantitative modelling. There were also quantitative components in interviews. b) Statistical analysis, modelling, input into systemic narratives.
6. a) Qualitative data gathering involved designing and undertaking structured, semi-structured and in-depth, open and closed, interviews and focus groups; reflections; and workshop processes which yield text: written or verbal recording that were transcribed. b) Thematic analysis, conceptual modelling.
7. a) Systemic narratives connected analysed data, and drew on the multiple lines of evidence and causal insights.

Data collection was conducted in terms of required ethical clearance from Rhodes University.

Principles for practicing Adaptive IWRM in South Africa: to transcend current practices, to transform, and to shape the future

PRINCIPLE:	ADDRESSES:
From the National Water Act: equity, sustainability and efficiency	Discrimination, unfairness, and wastefulness
Courage - transformation is revolutionary and radical	Current paralysis in the status quo
Consciously accept, understand and act in terms of the implications of CSES: - trust longer, winding journeys - watch out for and accept emergence - we can't know everything – all our knowledge is provisional so humility is essential - requisite simplicity - relationality and relationships are key drivers	Pitfalls of mistaken "efficiency" and arrogant knowledge
Foreground practice and learning by doing, changed behaviour arises from awareness and knowledge transfer	"Listen to me and do what I tell you"
Foreground the social	Habits of science only, and science superiority
Pay attention to context	Habits of stereotyping and seeking recipes that can be broadly applied
Use values and principles to guide contextual decision-making	Beliefs that stereotyped roles and recipes can be broadly applied
Pay vigilant attention to emancipatory and transformative potential	Convictions that: "the rules work and can be revised"
Pay attention to power relations	The powerful are happy with the status quo they created and benefit from it
Build on existing strengths and opportunities	Paralysis by enormity and tangledness* of problems
Cultivate consciousness and recognise "traps" of old practice - good facilitation can be helpful	That it is easier to ignore the implications of complexity and change
Work towards shared understanding	Starting with conflict
Work on challenges that bring people together	Paralysis by enormity and tangledness* of problems
Create a vision of a shared future (learn to be adept at moving between the challenges of the present and what will embody that future)	Paralysis by enormity and tangledness* of current problems
Recognise the power of citizen science and participatory governance	Acceptance that real participation is too hard and too expensive
Pay attention to learning opportunities: work-based learning for change; social learning where tensions create learning chances, and learning for capability (doing the task), rather than competency (understanding the task)	Changed behaviour arises from awareness and knowledge transfer
Engage and co-learn	Avoid engagement where you announce, and impart what is always only partial knowledge. Avoid just ticking "stakeholder engagement" box

* The metaphor we have come to use is that of the "knot": - When one tries to untangle a piece of fishing line picked up on the beach, tugging in one place often tightens another, and then there is the seaweed, or fishing hooks that have become entangled. At first a lot of energy goes into

loosening. In Adaptive IWRM the best we can often aspire to, is the conscious recognition of new options that arise as "knotty" problem areas are loosened, mindful of the future knots that will necessarily emerge. However, the team work, confidence and ability to take action, to monitor consequences and adjust direction become empowering ways of operating.

1.6 The role of Earth observation in the project

Hydrologists predict water supply by using models which rely on data from gauging weirs and a network of rain gauges (Agricultural Catchments Research Unit [ACRU] agrohydrological model: Schulze 1995; SPATSIM: Hughes and Forsyth 2002; SWAP: Kroes and Van Dam 2003). However, these models need to be parameterized for each catchment and this is problematic in un-gauged catchments. The DEA WfW Programme has demonstrated the importance of understanding the role of plant water use within a catchment (Blignaut et al. 2007). New techniques have been developed for improving the quantum of ET in water balances within catchments, and these can be used to inform management interventions in gauged as well as un-gauged catchments. Several examples of improving estimates of catchment scale ET have been developed and are strongly driven by input from satellite-borne sensors and programmes (SPOT, MODIS, Landsat, Copernicus). One of these, the MODIS, provides several products including the LAI (MOD15), which can be used to model ETa (MOD16) when combined with ground-based meteorological data, and MOD17, which models gross primary production.

The MODIS instrument was first developed after the Engineering Model was completed in mid-1995. Since then, it has become the key instrument aboard the Terra (EOS AM) satellite launched in 1999 and Aqua (EOS PM) satellite launched in 2004. The MODIS instrument makes it possible to expand ground-truthed ET measurements to larger scale with satellite imagery (Glenn et al. 2007). MODIS data is useful for the estimation of ET and surface soil water availability using vegetation index such as the normalised difference vegetation index (NDVI) and LAI (Nagler et al. 2005; Nishida et al. 2003; Venturini et al. 2008). These data can also be used to estimate canopy water stress index from the reflectance of MODIS multispectral bands (Fensholt and Sandholt 2003) and provide physical models with Earth observation information such as LAI (Zhou et al. 2004). The MODIS LAI product has been used in many validation studies and its accuracy is 0.66 LAI units root mean square error (RMSE) when all plants are included and it is 0.5 LAI units RMSE when broadleaf forests are excluded. The validation of MODIS LAI product has two parts, firstly the validation of LAI Radiative Transfer algorithm and secondly the accuracy of the LAI product by using empirical methods. These have been analysed and validated at several sites over the world (Hill et al. 2006).

Earth observation retrievals of LAI are affected by three primary variables which are: 1) uncertainties in surface reflectance product (due to corrections for atmosphere effects); 2) land cover identification (due to biome identification) and 3) geo-registration (Knyazikhin et al. 1998). Due to variations caused by uncertainties, the algorithm does not guarantee an accurate LAI value in one pixel and this can be reduced by averaging over a homogenous area or taking the best value of parameters to estimate the most probable value of LAI. Since the algorithm provides the distribution of LAI values as if they were derived from ground-based measurements, it is therefore important to use statistical techniques that can compare field-measured and satellite-derived LAIs to validate the MODIS LAI product. Ground-based validation techniques play a vital role in measuring uncertainties in the MODIS LAI product. Fuentes et al. (2008) used ground-truthed measurements of canopy LAI which was obtained using gap fraction analysis of upward-looking digital photographs at eight sites in Australian eucalyptus woodland to validate MODIS LAI.

Palmer et al. (2010) validated the predictions by the MODIS LAI-Stand Water Use (MODIS LAI-SWU) model they developed using data obtained from two catchments. The one in Northern Territory (Howard River), Australia had ground-truth measurements from eddy covariance (EC) flux data, sapflow and open top chambers which were compared with the MODIS LAI-SWU model predictions. In a gauged quaternary catchment in South Africa, ET was calculated from the available rainfall and runoff data and also compared with the predictions by MODIS LAI-SWU model (Palmer et al. 2010). Their results showed an acceptable comparison between the MODIS LAI-SWU model predictions and the EC data which led to the conclusion that the model can improve catchment scale estimates especially in un-gauged catchments (Palmer et al. 2008).

Leuning et al. (2005) showed that MODIS LAI can approximate the stomatal conductance component (g_s) of the Penman-Monteith (PM) equation and it was used in this study as an input into the PM equation (Gwate et al. 2018). The MODIS LAI estimates obtained are ground-truthed using the open top chamber (OTC) that sums up the water lost from the vegetation inside the chamber. MOD17 was selected as the primary source of LAI in several components of this project because it has a higher radiometric resolution than any other high temporal resolution products.

CHAPTER 2 ASSESSMENT AND RECOMMENDATIONS FOR IMPROVING THE GRASS PRODUCTION IN AREAS CLEARED BY THE WFW

by

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2.1 Assessing water use

Understanding the links between the control of undesirable woody plants and the derived benefits to humans occupying the catchment requires empirical evidence of the water use of the various components of the landscape. The landscape units or land cover types that are encountered in the mesic regions of South Africa are diverse, comprising inter alia areas of irrigation agriculture, dryland cultivation, residential, extensive rangeland and forests. Superimposed on this are two different land tenure systems (land use), namely freehold farms with a long history of commercial agriculture, and communal or leasehold areas, with diametrically opposing approaches to landscape management. Improved understanding of how to balance water use and carbon capture between different land cover types and land tenure systems is essential as they are important to people and their livelihoods. Therefore, this chapter deals with the overall project aim to assess and make recommendations for improving the grass production from areas that have been cleared of wattle by the WfW programme.

2.1.1 Methods

Defining production domains within a village

Identifying the production domains for LWP and improving flow efficiency across them offers an opportunity for smallholders to benefit by raising their income and alleviating poverty (Descheemaeker et al. 2010). High value goods and services are derived from water by livestock from various sources such as water consumed by drinking and water consumed through feeding. The amount of water consumed is determined by several factors related to the animal, feed and environmental conditions (Giger-Reverdin and Gihad 1991). Direct water consumption comprises only a relatively small part of total water budget. However, livestock ranching has a significant impact on water resources at landscape scale and watershed. Soil and vegetation degradation may result from the hydrological response of pastures and rangelands, which is affected by livestock grazing. Land degradation can be severe around watering points where livestock grazing pressure and trampling on vegetation can be noticed (Descheemaeker et al. 2010). In this study, areas where most grazing is taking place during wet and dry season were identified and sub-divided into different domains (Descheemaeker et al. 2010), using a combination of Earth observations and in-field boundary definition. Possible domains that were identified include a) unimproved grasslands (including riparian zones, wattle groves and areas removed of wattle), b) cultivated lands and c) immediately adjacent to homesteads (areas associated with livestock holding such as kraals). Domain boundaries were determined through geographic information systems (GIS) mapping techniques using remote sensing.

MODIS LAI and MODIS ET data

Both MODIS LAI and MODIS ET were extracted from the three identified grazing domains using a pre-processed MODIS imagery (MODIS 15A3) that were acquired from Land Processes Distributed Data Archive through GEE (Map data 2017 Google, INEGI, ORION-ME, USA). The domains were separated from each other by developing polygons on Google Earth that matched ground measurements. However, only ET from unimproved grasslands was used in this study. Maximum LAI values were calculated for each domain. According to Leuning et al. (2009) and Palmer et al. (2015), LAI can be integrated into the PM equation to predict actual evapotranspiration. A Java script with instructions to extract data for the entire length of the MODIS record from 2001-2017 was used for both MODIS ET and MODIS LAI. This provided the baseline of maximum LAI values retrieved for each domain. On the other hand, rainfall for the entire period (2001-2017) was also extracted was the automatic weather station at Cala. A detailed meteorological record for the whole 2016 period was used to calculate actual ET for the unimproved grassland to be included in the LWP denominator.

PMP equation

In this study we used the PMP equation (Palmer et al. 2015) which uses LAI as a proxy for vegetation indices to scale potential evapotranspiration (ET0) to ETa. Some form of convergent evolution in terms of strategies and functionality across biomes are shown by vegetation evolution where plants evolve to calibrate light harvesting ability and leaf area through the availability of resources to optimise carbon fixation. LAI is a main indicator of plant water use and vegetation physiology (Zeppel 2013). When plant root systems are able to supply water to the atmosphere through stomata at a rate almost corresponding to demand, ETa approaches ET0 under ideal conditions of abundant soil moisture and fertility (Gwate et al. 2016). However, this relationship degrades to some fraction < 1 when there is limited soil moisture. The PMP model was developed to maximum LAI ($\mathrm{LAI_{max}}$) which indicates the vegetation functional condition of a landscape relative to its optimum (Palmer et al. 2014). Furthermore, this relationship can be applied to relate ETa to ET0 assuming that ET0 represents the upper limit of water use possible within the system where $\frac{LAI}{LAI_{max}} = 1$. From a long-term data sets such as the MOD15A3 LAI product, maximum LAI can be derived. The underlying assumption is that under ideal conditions, efficiency levels are possible to the extent that all available energy defined by the ET0 (Allen et al. 1998) is used for ET. The PMP model is expressed as equation 2.1:

$$ET = \frac{LAI}{LAI_{max}} * ET_0 \qquad \text{Equation 2.1}$$

where $\mathrm{LAI_{max}}$ is the maximum LAI and ET0 is the potential evapotranspiration recorded by the automatic weather station.

Automatic weather station data

An automatic weather station situated at Cala (-31°52'59S, 27°68'95E) provided records of rainfall, temperature (maximum and minimum), radiation, relative humidity, wind speed direction and PET at an hourly or daily time step, and the station had a complete data record for 2016. Daily ET0 returns from the station were used to calculate ETa using the PMP (Palmer et al. 2015) for that time period.

2.1.2 Results

Evapotranspiration

MODIS LAI was extracted for unimproved grasslands, cultivated lands and areas around the homesteads in the study area which was integrated into the PMP equation to predict ETa. However, only ETa from unimproved grasslands was used to calculate LWP. Maximum LAI that were calculated for each domain ranged from 3.84 on *unimproved grasslands*, 4.1 on *cultivated lands* and 2.9 *around the homesteads*. MODIS ET for the three grazing domains is illustrated in Figure 2.1 and shows a mean annual MODIS ET of 428 mm for unimproved grassland, 421 mm for cultivated lands and 425 mm for areas around the homesteads. On the other hand, mean rainfall of 636 mm was also extracted from the study site for the 2001-2017 period. The actual ET calculated using PMP equation for the year 2016 was 270 mm for the unimproved grasslands, while MODIS ET for unimproved grassland in 2016 was 378 mm.

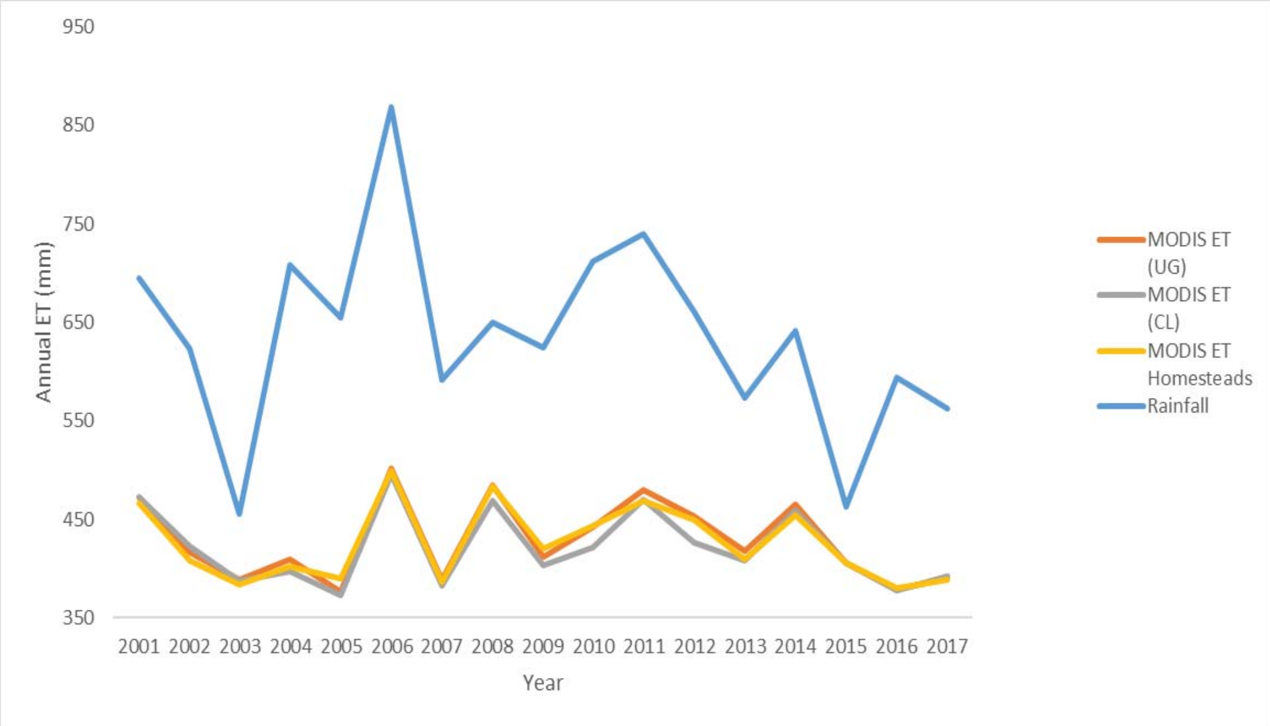


Figure 2.1 The mean monthly evapotranspiration for three grazing domains in Mgwalana village for the year 2001-2017. UG - unimproved grasslands, CL - cultivated lands.

2.1.3 Discussion

Evapotranspiration

Apart from runoff and precipitation, the principal part of a hydrological cycle in semi-arid and humid regions is evapotranspiration which affects both environmental and biophysical processes at the interference between vegetation, atmosphere and soil (Mu et al. 2004). The actual evapotranspiration reflects a combined effect of all climatologic factors that can be seen as seasonal variations in different domains, which is caused by the differences in monthly variations of total energy available to drive ET. This study used a PMP equation to calculate ETa, which uses maximum LAI and potential ET to calculate actual ET. Similar to Palmer et al. (2017) maximum LAI of 3.84 was reported for unimproved grasslands. Maximum LAI for other domains were 4.1 in cultivated lands and 2.9 in areas around the homesteads. On unimproved grassland PMP ETa of 270 mm was estimated for the year 2016, while MODIS ET for the year 2016 was 378 mm on unimproved grasslands. MODIS ET further reported a mean ET of 428 mm for the period of 2001-2017. This is because ETa is dependent on water and the amount of energy that is available to drive ET. The study was conducted in a dry land where no irrigation is taking place and severe water limitation occur in the dry season. The LAI of vegetation is highly temporally and spatially variable depending on seasonality, prevailing site condition, species composition, development stage and management practices

(Dantec et al. 2000). LAI further characterise energy absorption capacity and canopy function, which is a key parameter in most ecosystem productivity (Sellers et al. 1997).

The amount and timing of precipitation in semi-arid rangelands is an important driving force for evapotranspiration fluxes. A differences between MODIS ET and PMP ET in the study site was found, where MODIS ET was higher than PMP ET. Although maximum LAI in the study area was higher than 2.5, Gwate et al. (2016) argue that, estimating ET from LAI may be reliable when LAI values < 2.5, which applies to most retrievals. This study estimated 56% less ET using the PMP than the MODIS ET. This can be due to short grass canopies that are be less effective in capturing energy through the leaf canopy to the soil. Although LAI_{max} in the study area was 3.84, the PMP model could not capture changes in ET and underestimated PMP ET compared to MODIS ET. Similar results were found, where PMP ET underestimated ET in the Albany thickets of South Africa (Gwate et al. 2016). MODIS LAI over grasslands does not respond rapidly to the rainy events leading to compromised PMP ET predictions. Even though the PMP model underestimated ET, it was found to be best performing in the semi-arid savanna of South Africa (Palmer et al. 2015) where there was much greater woody component. Furthermore, variations in PMP ET and MODIS ET suggests that the rate of change in ET might not be consistent with that of precipitation because factors such as land cover and land use change have a role in the hydrological balance of the landscape. Tian et al. (2010), reported a change in ET over time in terrestrial ecosystems of the southern United States during 1995–2007, with semi-arid terrestrial ecosystem using a greater proportion of precipitated water than more mesic ecosystems. The fact that MODIS ET >> PMP ET, and that for these sub-humid grasslands, ET should be closer to precipitation, it was decided that MODIS ET should be used for all further analysis.

2.2 Assessing grass production

2.2.1 Methods

Estimating vegetation cover and Above-ground Net Primary Productivity (ANPP)

A non-destructive method (Flombaum and Sala 2007) was used to determine ANPP in which dry matter biomass was estimated using vegetation cover. Grass canopy cover was measured using the line intercept method from a total of 21 X 100 m transects in 2014-2016 during the month of April. The samples were collected on a continuously grazed site. Following Flombaum and Sala (2007), all above-ground biomass was harvested after every 20 m adjacent to the 100m transect on a 0.2 m^2 (1.0 x 0.2 m) quadrat. Visual assessment of the cover was estimated based on the area covered in the quadrat. To get the dry matter weight, grass biomass samples from each quadrat were harvested and later dried in an oven at 70°C for three days. Simple linear regression was constructed to estimate grass dry matter biomass from vegetation cover.

Estimating ANPP and calibrating DPM

To describe the biophysical attributes of the ecosystem in communal rangelands, six grazing exclosures (2.25 m^2) were established in a communal grazing land (T12A). Data form exclosures that were established in another communal grazing land (S50E) and a commercial grazing land (T35B) (Gwate 2018) was also used. During the month of June 2014, the exclosures were established and were clipped to 2 cm above the soil surface and were protected from grazing. In May 2015 and 2016, nine points were sampled using the DPM (Bransby and Tainton 1977) within each exclosure, and the grass biomass below the plate (0.166 m^2) was clipped to 2 cm. Furthermore, the DPM readings were recorded at the settling height for each sample. To determine the dry grass biomass, the clipped sample was oven dried at 70^o C for three days. The DPM was calibrated using a simple linear regression of grass biomass dry matter against settling height.

Assessment of Net photosynthesis (PsnNet)

The effective measurement of carbon and water fluxes in different land covers is very important as they differ in the capacity to utilise above and below ground biomass. Net photosynthesis of a pure natural grassland was extracted from pre-processed MODIS imagery which was acquired from Land Processes Distributed Data Archive, GEE (Map data 2017 Google, INEGI, ORION-ME, USA). The time series data for MODIS PsnNet was acquired using a Java script with instructions for the period of January 2000 to August 2017 (Figure 2.2). Mean annual carbon produced by the landscape was calculated. Incomplete dataset for the year 2015 and 2016 was completed through data gap filling following Koutsoyiannis (2011).

Figure 2.2 The location of the area from which values for MODIS PsnNet products were extracted at the Mgwalana village

2.2.2 Results

Relationship between ANPP and vegetation cover

Figure 2.3 Illustrates the relationship between the grass biomass production and the percentage cover of grasses along a 100 m transect. There was a wide range of variation between grass biomass production and vegetation cover. There is a positive relationship between vegetation cover and grass biomass production. The regression was forced through zero because in quadrants where there is no grass biomass, the estimated cover was zero. The regression equation revealed a slope of 88.5 with R^2 of 0.96 ($p < 0.001$). The mean canopy cover was 64% in T12A, while canopy cover from other sites (S50E) and (T35B) was 71% and 65% respectively. The mean canopy cover was then used to predict the above-ground primary production within the respective sites.

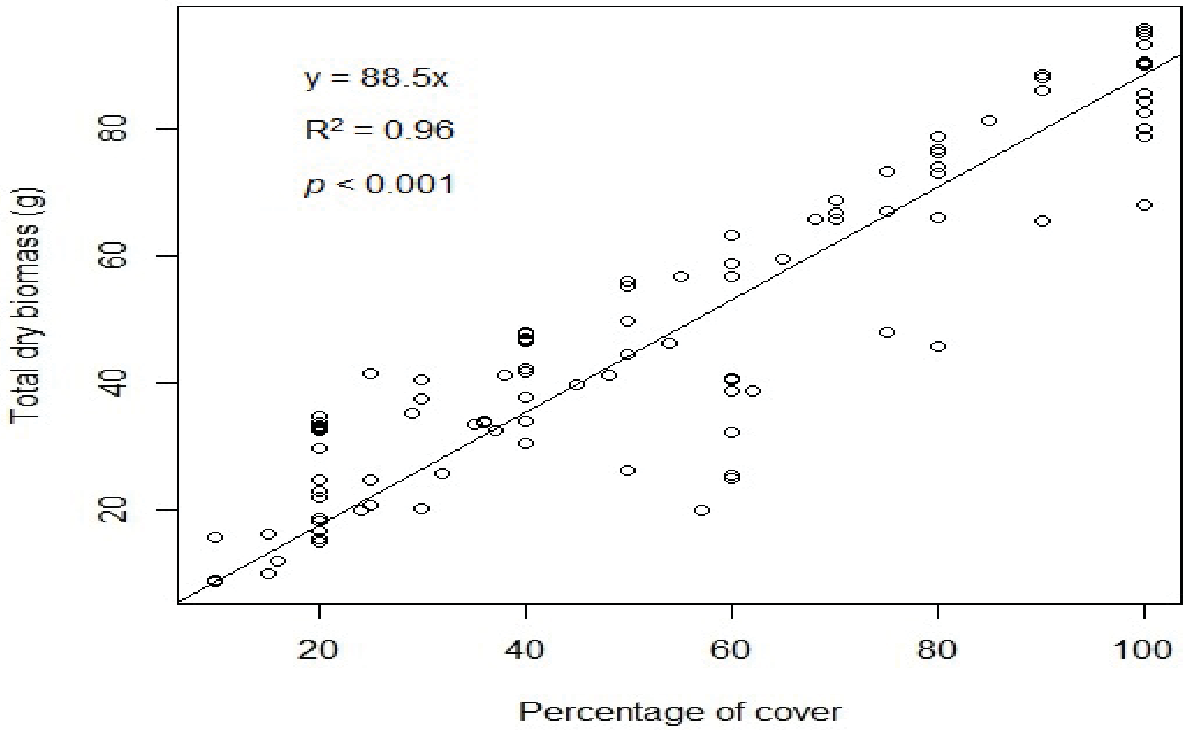
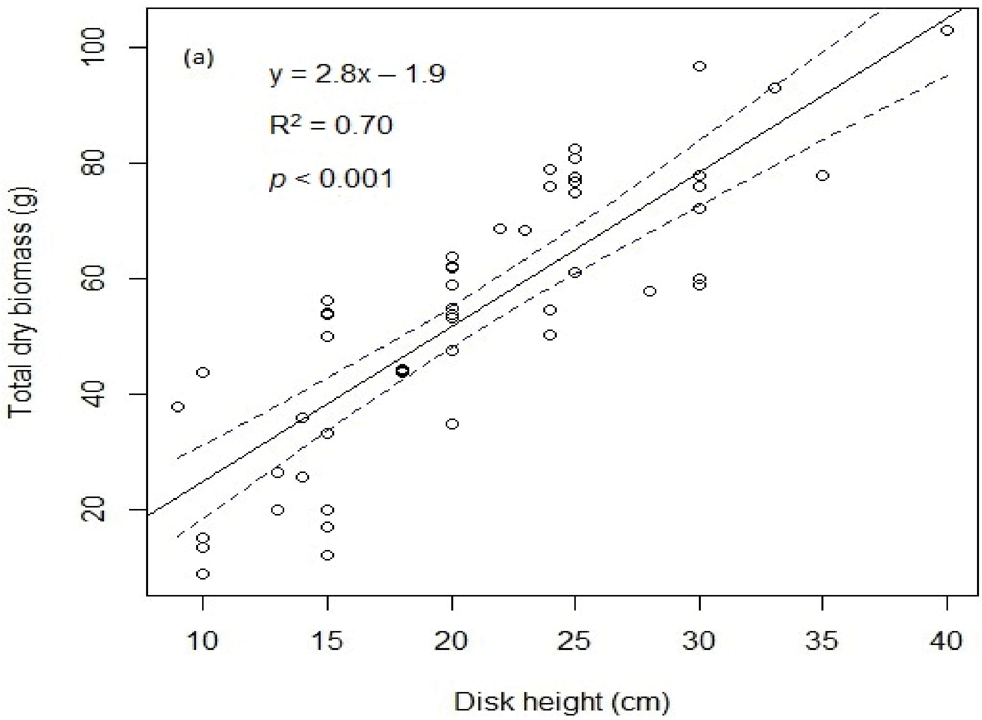


Figure 2.3 The relationship between above-ground grass biomass and grass cover from 105 0.2 m^2 sub-plots along twelve 100 m line transects

Calibration of ANPP and DPM

Figure 2.4a illustrates mean disc pasture meter settling heights and total above-ground grass biomass in the study site within the quaternary catchment T12A. Figures 2.4b and c, also illustrates the mean DPM settling height in other two quaternary catchment which were used for comparison (S50E) and (T35B) respectively. The mean DPM settling height of 16.39 cm was recorded in T12A, followed by 19.53 cm in S50E and 20.93 cm in T35B. Although, the mean DPM readings were significantly different ($p<0,001$) among the sites, a positive relationship was revealed as the increase in disc pasture meter reading increase with the increase NPP.



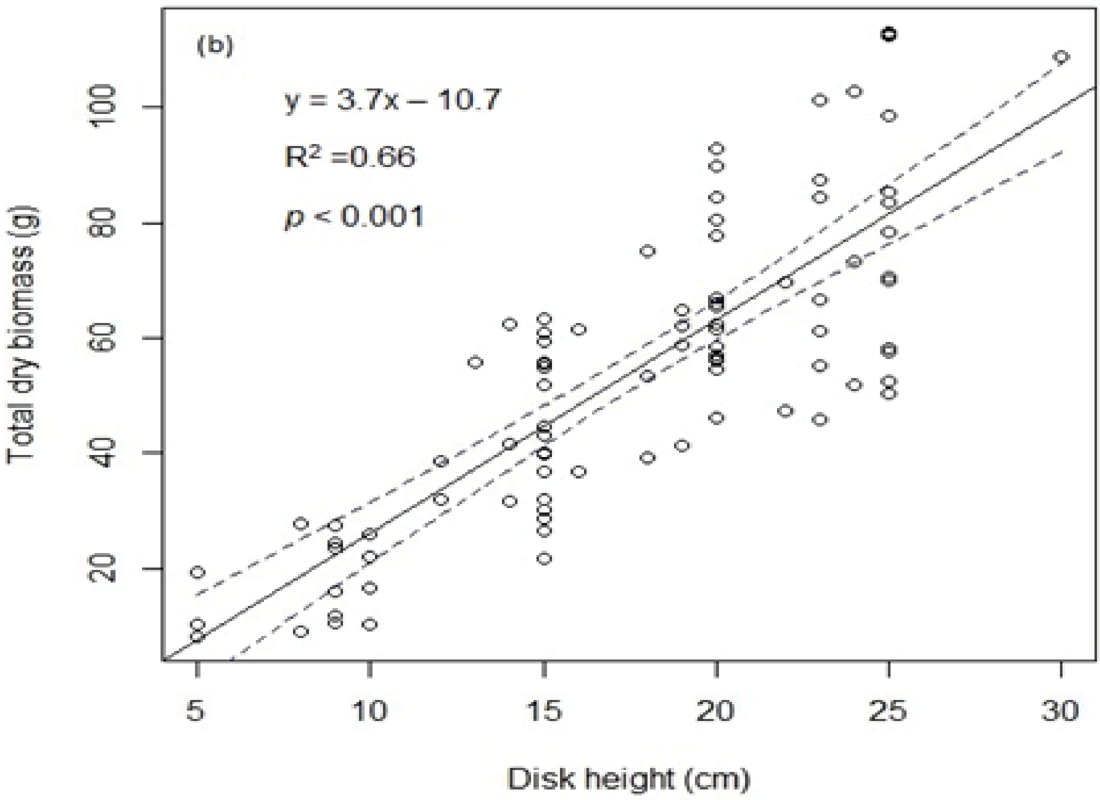


Figure 2.4 Calibration of the above-ground biomass and the DPM reading at three sites a) Communal grazing land, b) Communal grazing land.

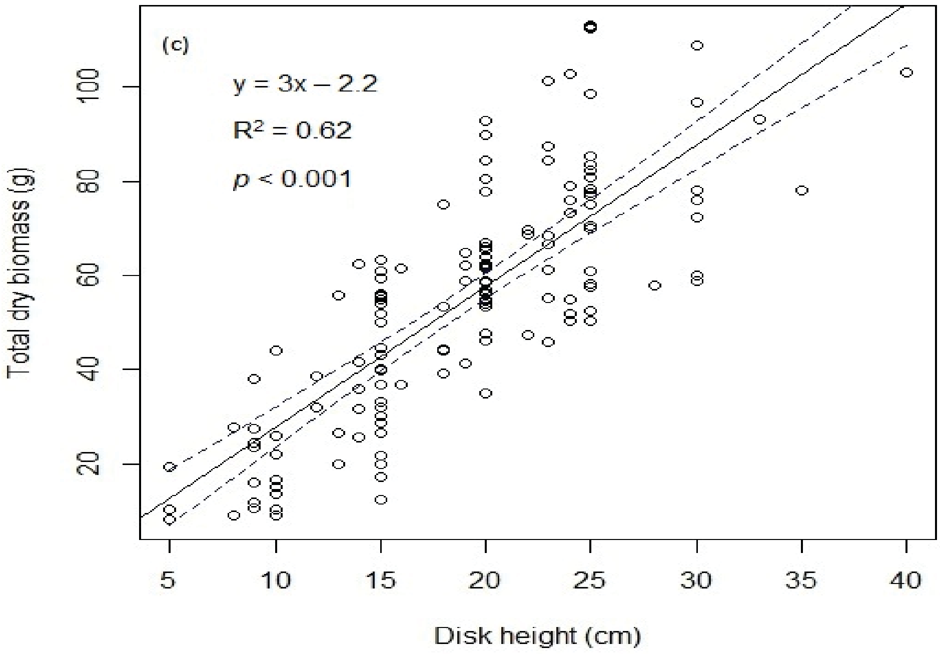


Figure 2.5 Calibration of the above-ground biomass and the DPM reading at three sites c) Commercial grazing lands.

Relationship between DPM and line intercept

Table 2.1 shows the DPM readings and the predicted ANPP using line intercept for the study site. ANPP of 370 g dry mass (DM) $m^{-2}yr^{-1}$ was estimated based on the DPM settling height. The average DPM readings further estimated a line intercept prediction of 220 g DM m^{-2} yr^{-1}. Compared to S50E and T35B, the DPM predicted ANPP of 324 g DM $m^{-2}yr^{-1}$ in S50E and 348 g DM $m^{-2}yr^{-1}$ in T35B lower than T12A, while the line intercept predicted 314 g DM $m^{-2}yr^{-1}$ and 288 g DM $m^{-2}yr^{-1}$ in S50E and T35B respectively (Table 2.1). Results from other studies such as those conducted by (O'Connor 2008; Everson and Everson 2016; Danckwerts and Trollope 1980) were used in this study for comparison.

Table 2.1 Relationship in the dry matter between DPM and the line intercept

Site	Location	Mean Annual Rainfall (MAR) (mm)	DPM Above-ground grass biomass g DM m^{-2} yr^{-1}	Line intercept Above-ground grass biomass g DM m^{-2} yr^{-1}
S50E (Gwate et al. 2016)	31°40'41S 27°35'12E	772	324	314
T12A	31°31'25S 27°45'27E	655	370	220
T35B (Gwate et al. 2016)	31°04'05S 28°17'34E	786	348	288
Danckwerts and Trollope (1980)	32°42'05S 26°27'18E	409	252	N/A
O'Connor (2008)	29°45'01S 29°33'07E	893	292	N/A
	29°49'01S 29°37'57E	862	244	N/A
Everson and Everson (2016, biennial burnt)	29°56'17S 29°15'41E	880	471	N/A

Net photosynthesis for the best condition unimproved grassland.

Net photosynthesis (PsnNet) was extracted from MODIS for the best condition unimproved grassland at T12A (Figure 2.5). It shows how constant the production of this site is over the past 17 years (2000-2017). The mean annual carbon of 880.7 g C m^{-2} yr^{-1} for the unimproved grassland was calculated from the data represented in Figure 2.5.

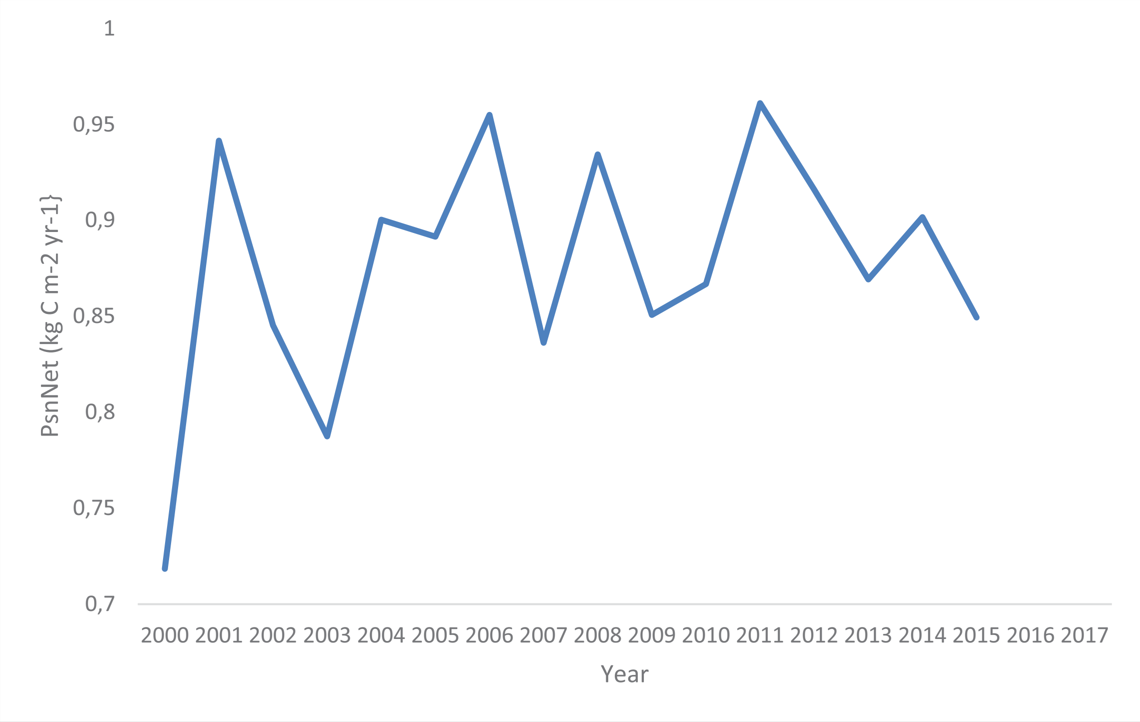


Figure 2.6 The net photosynthesis for the unimproved grassland in T12A (Mgwalana village)

Grass biomass and vegetation cover

A positive relationship was revealed between the vegetation cover and dry grass biomass through a 100 m transect. A non-descriptive method to calibrate the estimation of above grass biomass measuring vegetation cover was used in this study, which can be used to replace the grass harvesting method because it allows for multiple estimates of biomass in the same area and is cost-effective (Sala and Austin 2000). It can be used as an alternative to harvesting grass through estimating it using the variables that correlate with it such as vegetation cover. The study results were similar to those found by Flombaum and Sala (2007), who reported that cover was a good predictor of ANPP, vegetation cover and green biomass. ANPP and vegetation cover have inter-annual variation which are affected by the distribution patterns and amount of precipitation (Vandandorj et al. 2015).

Relationship between the DPM and the predicted ANPP

The amount of herbage available for grazing is of crucial importance for animal production. The regression equation (Danckwerts and Trollope 1980) was developed to convert the DPM readings of the standing biomass measurements which expressed the amount of forage at a given time in a rangeland, however it is not a measure of production of grazable material through a growing season. In this study, the DPM ANPP of 370 g DM m^{-2} yr^{-1} was reported on unimproved grasslands, with the line intercept predicting ANPP of 220 g DM m^{-2} yr^{-1}. The regression equations developed were similar to other studies (Flombaum and Sala 2007). Using results from Gwate et al. (2017) on other communal (S50E) and commercial (T35B) rangelands, the disk pasture readings were 324 g DM m^{-2} yr^{-1} and 348 g DM m^{-2} yr^{-1} respectively, this implies that the lower standing biomass in communal areas does not equate to lower productivity as communal areas are as productive as commercial areas. The line intercept and the DPM reading revealed a good relationship in validating the ANPP, which provided an easy technique to estimate grass biomass for an improved grazing management. The ANPP predicted in this study were similar to other estimates reported in natural grasslands such as those found by O'Connor (2008) in commercial and communal rangelands of the southern Drakensberg area. However, Everson and Everson (2016) estimated ANPP values ranging from 190 g m^{-2} yr^{-1} for montane grassland exposed to annual winter burning to 471 g m^{-2} yr^{-1} for grasslands exposed to two yearly burning using long-term data. Further more, (Danckwerts and Trollope 1980), reported ANPP of 252 g DM m^{-2} yr^{-1}.

Precipitation is the primary constraint to ANPP in grasslands because it is an ecosystem driver of ongoing climatic change (McAuliffer 2003). Results of this study revealed the effect of rainfall gradient on ANPP with high rainfall areas matching with higher ANPP compared to lower rainfall areas. This is similar to McAuliffer (2003), who states that shifting patterns in precipitation with increase surface temperature have a direct impact on the hydrological cycle of water. However, studies such as those conducted by O'Connor (2008) and (Everson and Everson 2016) imply that other factors such as burning and grazing play a greater role than precipitation alone. High ANPP in these study sites could possibly be due to the nutrient extraction in the soil due to the removal of IAPs in areas where the exclosures were established (Gwate et al. 2016). The NPP in rangelands is one of the important components of global carbon cycle. The spatial variability of NPP over the globe is enormous, ranging from 1000 g C m^{-2} for an evergreen tropical rain forest to less than 30 g C m^{-2} for desert (Baldocchi et al. 2018). In this study there was no discernible trend that could be linked to a continually degrading rangeland. The annual long-term mean PsnNet of 880g C m^{-2} per annum and the lack of trend retrieved from MOD17A3 indicates that the selected domain represents a healthy grassland showing no signs of degradation.

2.2.3 Discussion

Improving rangeland productivity through grazing management is one possible way of improving LWP. An adaptive stocking density and appropriate herd composition may positively influence vegetation ground cover, species composition and NPP, thus improved water use. In this study, we described the biophysical attributes of the ecosystem in a communal rangeland where everyone has an equal access and no proper grazing management is followed. This study supports an estimated annual ET for 2016 over the unimproved grasslands of 378 mm (MOD15), which will be used in all further analysis of LWP. Canopy cover was found to be a good predictor of above-ground dry grass biomass production in heavily grazed ecosystems. The ANPP was comparable to other studies conducted in across South Africa and shows that rangeland production does not depend on the tenure system as communal rangelands were as productive. This implies that many factors exist that determine the annual herbage production other than grazing. Therefore, there is a need for proper grazing management plans to be put in place to prevent excess water loss on communal rangelands. The disc pasture meter can be a useful management tool to be used by poor resource farmers, this will be important as it will allow them to graze and rest their rangelands at a proper time for the next growing season.

2.3 A novel approach to deriving land use productivity using GEE

2.3.1 Background and rationale

GEE is a geoprocessing cloud platform that combines a catalogue of online satellite imagery and geospatial datasets with global-scale analysis capabilities (Gorelick et al. 2017). Users can run geospatial analyses on Google's Cloud infrastructure, providing a wide range of practical benefits over traditional approaches i.e. no costs, desktop software, intensive processors or downloaded imagery is required. GEE is utilised across a wide variety of disciplines and has also been integrated into a number of web applications.

The documented research methods for modelling land use productivity mainly involve applying a model to downloaded satellite imagery using desktop-based geoprocessing software operated by expert users. Modern technologies, implemented via e.g. smartphones offer opportunities of acquiring real-time field data to assist in planning and further calibration of theoretical and simulated models.

2.3.2 Methods

GEE was combined with mobile application development platforms to determine accurate, in-field estimations of land use productivity. Using theoretical and empirical equations in existing literature (Allen et al. 1998; Guevara et al. 1997; Palmer et al. 2017; Running et al. 2004) an NDVI-LAI-NPP model for estimating land use productivity for grassland was developed and executed in GEE using Python scripts and the GEE online archive of satellite imagery following the workflow documented in Figure 2.6.

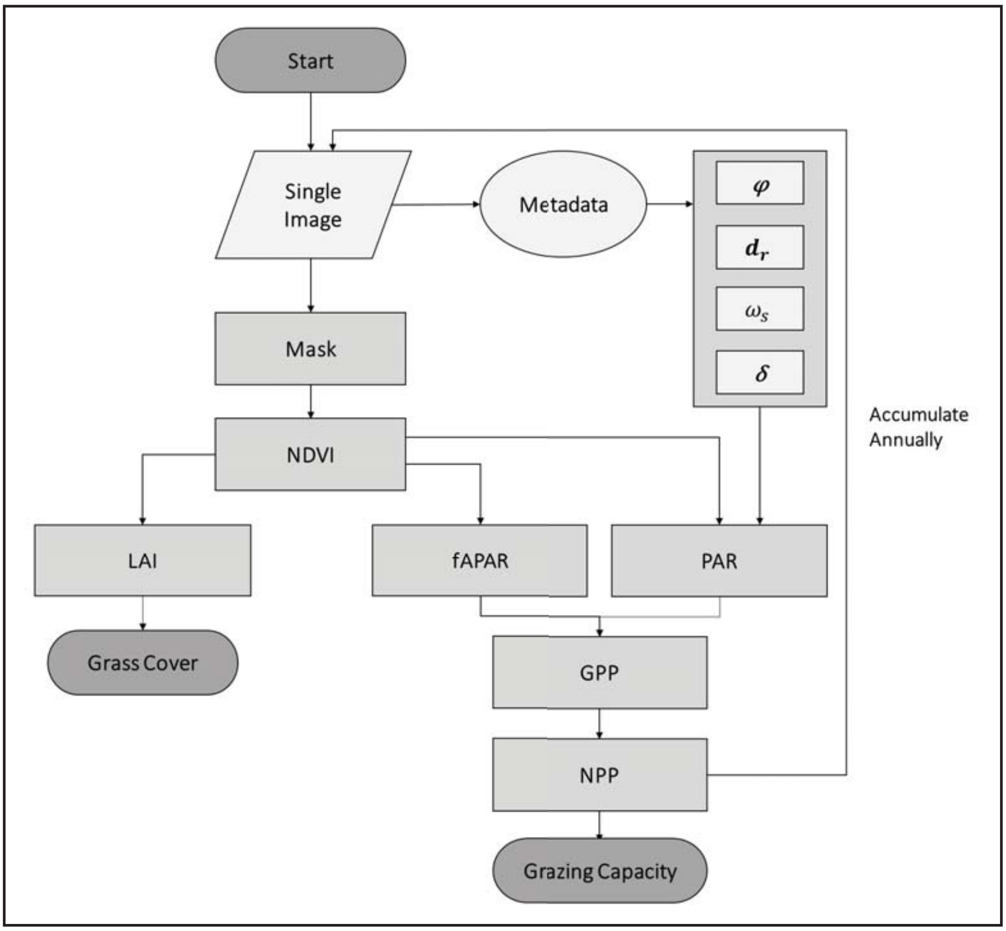


Figure 2.7 NDVI-LAI-NPP model

The functionality of the NDVI-LAI-NPP model was packaged in a mobile application to allow in-field estimations of land use productivity. Due to accessibility constraints of GEE, which requires authentication via a web application backend to utilise geoprocessing functionalities in an application environment, a hybrid mobile application was developed that allowed porting a web application to a fully-functioning mobile application. The overall business logic of the different application components is illustrated in Figure 2.7.

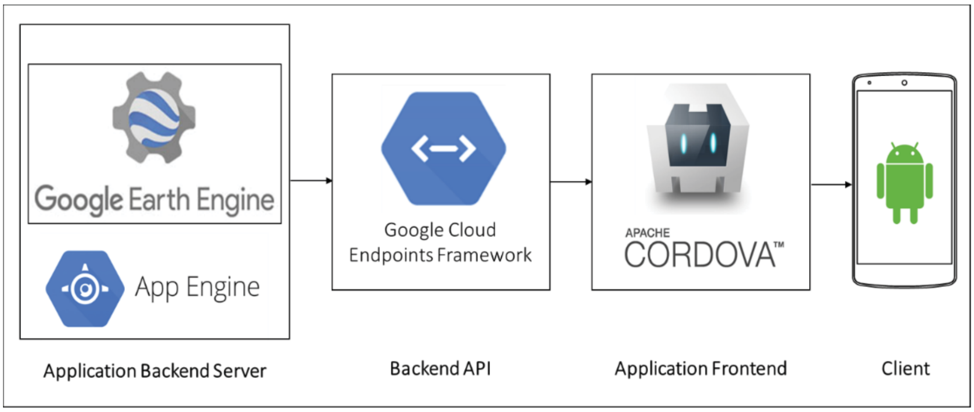


Figure 2.8 Application business logic

2.3.3 Results

Maps were produced for intermediate and final products generated by the NDVI-LAI-NPP model (Vermeulen et al. in press). Figure 2.8 shows the model-estimated grazing capacity (ha LSU^{-1}) for Landsat 8 and MODIS.

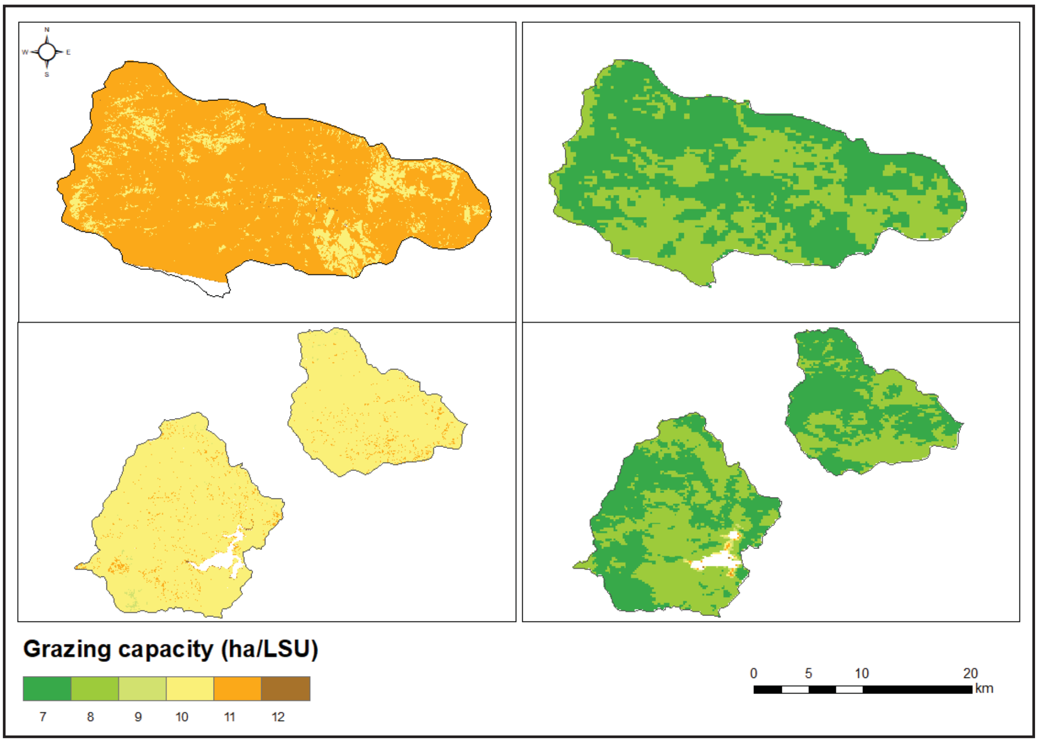


Figure 2.9 Model-estimated annual grazing capacity (ha LSU^{-1}) for Landsat 8 (left) and MODIS (right)

The output was symbolised according to the national grazing capacity map of 2009 (Ngwenyama 2009). Quite a big difference can be seen between the Landsat 8 and MODIS results. Landsat 8 produced higher estimations of grazing capacity, ranging from 9-11 ha LSU^{-1}, whereas MODIS estimated values ranging from 6-8 ha LSU^{-1}.

Some examples of the mobile application user interface are provided in Figures 2.9 – 2.11.

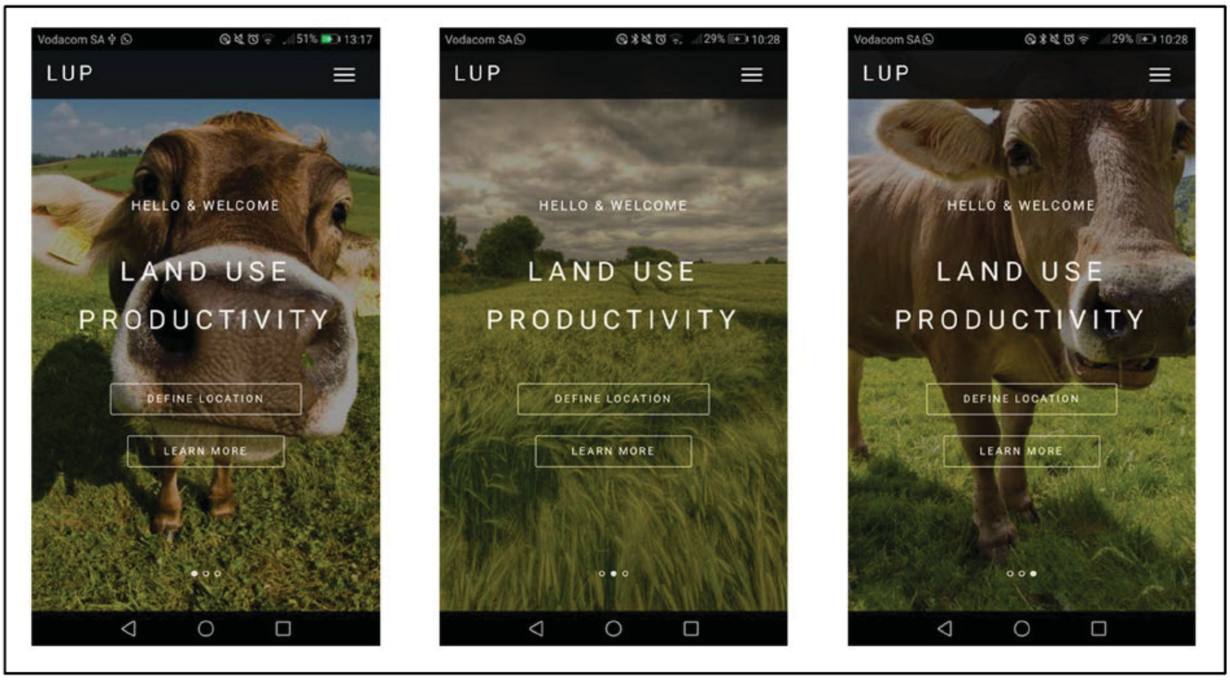


Figure 2.10 Example user interfaces for landing page

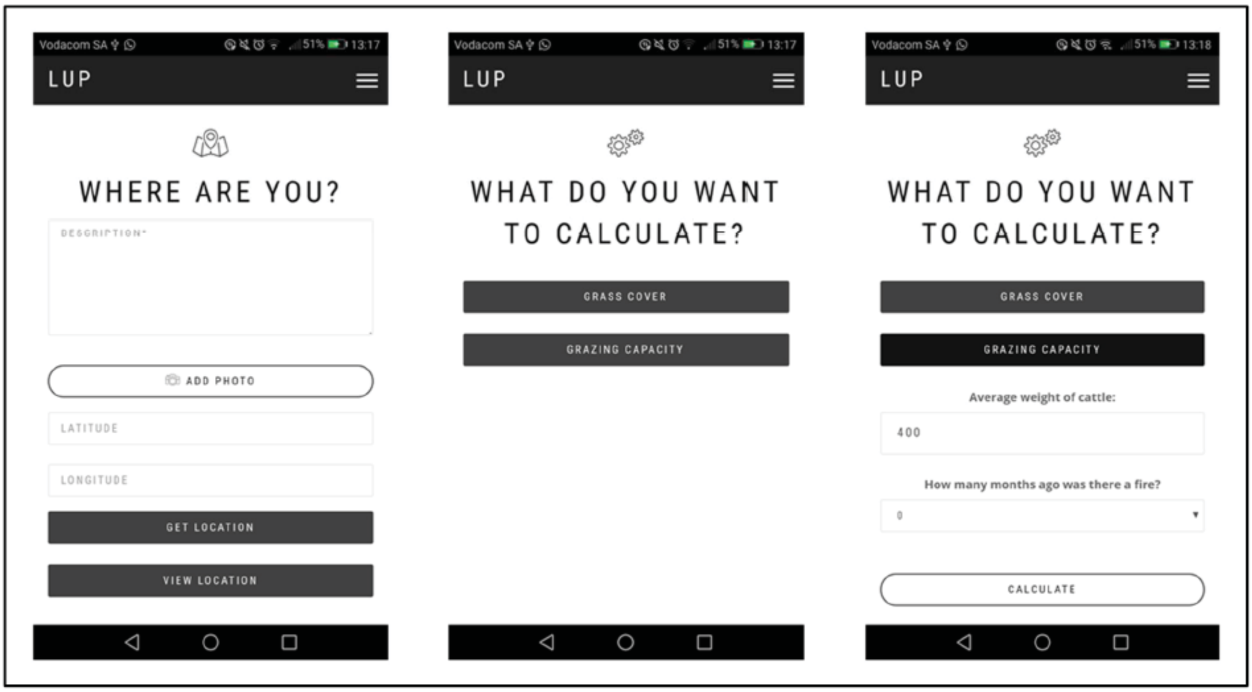


Figure 2.11 Example user interfaces for input of parameters

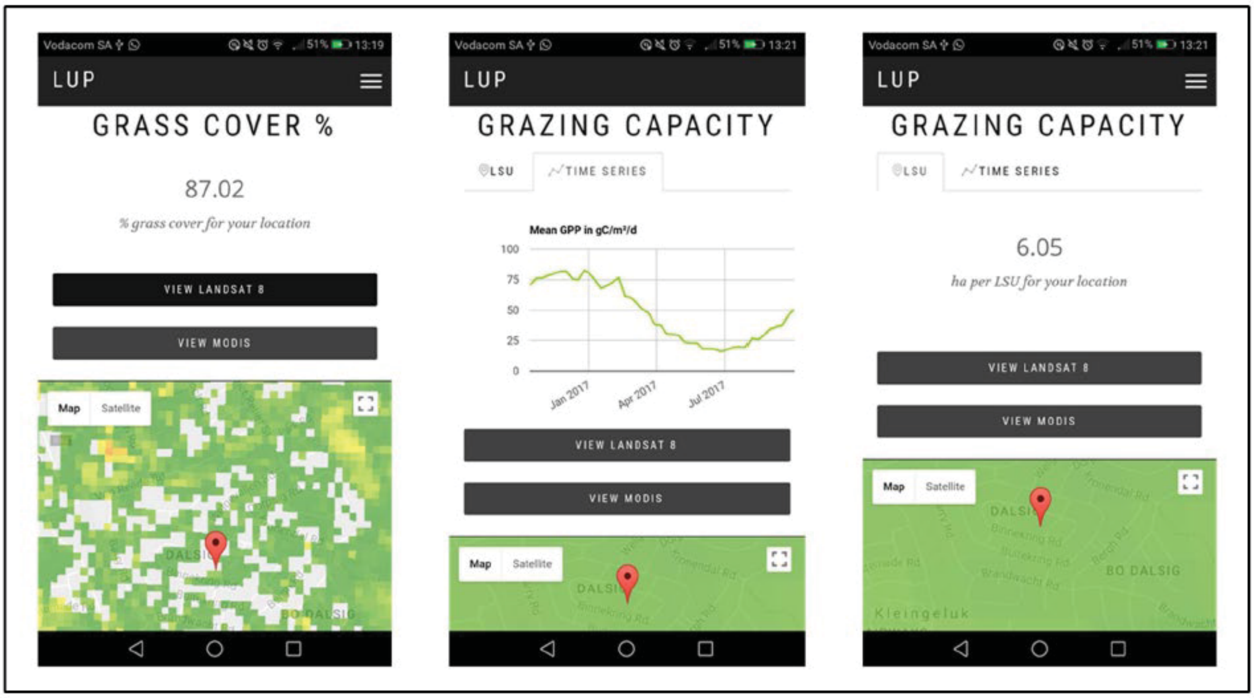


Figure 2.12 Example user interfaces for results

2.3.4 Discussion

By harnessing the benefits of these modern technologies, a novel approach was developed to efficiently calculate land use productivity derivatives in the field. Additional work is required with in-field testing to improve the accuracy of the results.

In the results, productivity (Gross Primary Productivity [GPP], NPP and grazing capacity) derived from Landsat 8 were consistently underestimated due to partial accumulation over a year and influence of low quality images, e.g. cloud cover. The underestimation of productivity by Landsat 8 resulted in overestimated grazing capacity results and grazing conditions in the study area were classified as poorer than expected by the reference map. MODIS, however, produced good grazing capacity results. Despite underestimation in Landsat 8, the grazing capacity estimations showed a strong linear agreement with the reference map (Ngwenyama 2009). The Landsat 8 estimations could thus potentially produce accurate results if more accurately modelled and accumulated.

However, this approach can provide non-expert users with a means of estimating in-field land use productivity for grasslands. The use of such a tool can therefore aid in the development and improvement of existing land use productivity models and sustainable managements systems for grasslands, especially if additional in-field parameters can be captured. Further work on improving the model by implementing a fractional cover layer is underway as part of a Master's thesis.

2.4 Assessing soil characteristics after wattle clearing

2.4.1 Methods

Soil sampling

Soil samples were collected during the period of 26 to 29 June 2014. Four sampling sites were identified, two in each of quaternary catchments T12A (sites 3 and 4 in communal lands) and T35B (sites 1 and 2 in commercial farming areas). At each site, three invasion statuses including recently-cleared area, un-cleared areas inside the *A. mearnsii* thicket; and a control in the adjacent, uninvaded grassland, were identified. These three invasion classes were each separated by a distance of 25 m. At each invasion class, three replicate samples were collected using a handheld soil auger. The replicates were separated by a distance of approximately 2 m. Soil samples were collected at 10 and 20 cm depths at each point. For each invasion class, 18 samples were collected, making a total of 72 samples. The samples were taken to the Soil Analytical Services Laboratory at Dohne Agricultural Development Institute, Stutterheim, South Africa for analysis. These samples were analysed for P, K, N, Mg, Ca, Zn, acid saturation, CEC, bulk density, pH and total cations. These variables were selected since they are critical indicators of soil recovery after degradation (Costantini et al. 2016). The analysis was performed following the AgriLaboratory Association of Southern Africa Handbook (AgriLASA Soil Handbook 2004) guidelines.

Soil statistical analysis

In order to reduce errors, soil samples data were analysed using a generalised linear model with site and invasion status as explanatory variables. If the main factor was significant, the posthoc Tukey's honest significant difference (HSD) test was used to investigate which sites or invasion status were different. In addition, Principal Component Analysis (PCA) with an orthogonal rotation of the axes (varimax rotation) was performed to reduce the number of soil variables accounting for variability in soil status across the sites under the R version 3.1.3 environment by exploiting the *vegan* package (Oksanen et al. 2017). Varimax rotation enables each variable to load heavily on as few components as possible to make interpretation easier (Linstädter and Baumann 2013). PCA was performed on the correlation matrix since units of raw data measurements differed. The scree-plot technique was used to identify the appropriate number of principal components to be extracted with eigenvalues greater than one.

2.4.2 Results

Effects of invasion status and site on soil variables

Multivariate tests showed that the invasion status (cleared, invaded or uninvaded), site factor and the interactive effects of the two had significant effects on the selected soil variables ($p < 0.001$, Table 2.2) and this allowed for further analysis of the between subject effects.

Table 2.2 Effects of sites, invasion status and interactive effects of invasion status and site on the soil variables

	Wilks' Lambda	*F*-statistic	Hypothesis *df*	Error *df*	p-value
Invasion status	0.24	4.59	22	102	<0.001
Site	0.03	9.87	33	148.01	<0.001
Invasion status and site	0.030	3. 83	66	2723	<0.001

The invasion status had statistically significant effects on P, K, N, CEC, total cations, acid saturation and pH ($p < 0.05$, Table 2.3) whereas marginal significant differences were detected for Mg and Zn ($p < 0.1$, Table 2.3). The P was higher in the invaded compared to soils in both cleared and uninvaded areas. Highest K, CEC, N, Zn and total cations were observed in the invaded followed by the cleared and finally the uninvaded areas. Bulk density was lower in the cleared compared to the invaded and uninvaded sites. On the other hand, Ca, Mg and pH were highest in the uninvaded areas while acid saturation was highest in the cleared (Table 2.3). The posthoc HSD revealed that P was significantly different in invaded and uninvaded areas ($p = 0.02$) and with respect to K, statistically differences were detected in cleared and invaded sites ($p = 0.04$). At the same time, pH ($p < 0.001$) was significantly different between the cleared and uninvaded sites while Mg ($p = 0.09$) was marginally different ($p < 0.1$) between these sites. In addition, pH ($p < 0.001$), CEC ($p < 0.001$), total cations ($p = 0.01$), acid saturation ($p = 0.006$), N ($p = 0.003$) were significantly different ($p < 0.05$) between uninvaded and invaded areas. Furthermore, CEC ($p < 0.001$), N ($p = 0.04$), acid saturation ($p = 0.004$) were significantly different between cleared and invaded sites. Finally, total cations ($p = 0.08$) and Zn ($p = 0.08$) were marginally different between cleared and invaded areas ($p < 0.1$).

Table 2.3 Effects of invasion status on soil variables (mean ± standard deviation, N = 24). Soil properties at 10 – 20 cm depths calculated by invasion status. Entries in bold indicate significant statistical difference at p < 0.05, while * highlights statistically insignificant differences and letters in round parenthesis indicate marginal significance at p < 0.1. Letters shared in a row indicate statistically insignificant differences and letters not shared highlight statistically significant differences according to the Tukey's HSD posthoc test.

Variable	Cleared	Invaded	uninvaded	df	*F*-statistic	p-value
Bulk density (g mL^{-1})	1.2 ± 0.1	1.9 ± 2.3	1.9 ± 2.5	2	1.3	0.27*
P (mg L^{-1})	11.5 ± 9 **a**	22.8 ± 36.4 **b**	7.1±5.4 **ac**	2	4.2	**0.022**
K (mg L^{-1})	95.7±54.7 **a**	132.5 ± 64.3 **b**	124.2 ± 61 **ab**	2	3.5	**0.038**
Ca (mg L^{-1})	328± 188.6	314 ± 261.9	376.46 ± 156.4	2	0.8	0.450*
Mg (mg L^{-1})	29.4± 37.3 (a)	49.8±65.6 (b)	51.7 ± 35 (b)	2	2.7	0.075
CEC (cmol L^{-1})	3.5 ± 1.1 **a**	3.7 ± 1.4 **ab**	2.47 ± 0.1 **c**	2	13.2	**<0.001**
Total cations (cmol L^{-1})	5.6±1.4 **a**	6±1.2 **ab**	5.1±1.1 **c**	2	6.6	**0.003**
Acid saturation (%)	63.9 ± 18.7 **a**	63.3 ± 23.8 **ab**	48.9±15.6 **c**	2	7.1	**0.002**
pH (KCl)	3.7 ± 0.24 **a**	3.71 ± 0.2 **b**	3.9 ± 0.2 **ac**	2	13.2	**<0.001**
Zn (mg L^{-1})	1.6 ± 1.3 a	3.6±6.3 b	3.175 ± 4.92 b	2	2.7	0.074
N (kg ha^{-1})	0.18 ± 0.04 **a**	0.21 ± 0.05 **ab**	0.18 ± 0.04 **ac**	2	6.4	**0.003**

According to Analysis of Variance (ANOVA), only K, Ca, N and total cations were statistically different between the 10 and 20 cm depths (p < 0.05). With respect to these variables higher values were observed at the 10 cm depth compared to the 20 cm one.

Effects of site on soil variables

The site factor had a significant effect (p < 0.05) on bulk density, Ca, Mg, CEC, total cations, acid saturation, pH, N, Ca and Zn while marginally significant differences (p < 0.1) was detected with respect to K (Table 2.4). Tukey's HSD posthoc comparisons revealed that site

1 and 2 (both commercial, T35B, p = 0.021), sites 2 and 3 in communal lands, T12A (p = 0.03) as well as sites 2 and 4 in communal lands T12A (p = 0.04) were statistically different with respect to bulk density. In terms of P, statistically significant differences were detected at sites 3 and 4 (p = 0.01) while marginal differences were observed at sites 2 and 4 (p = 0.06). With respect to Ca, sites 2 and 4 (p = 0.04) were statistically different while sites 2 and 3 (p = 0.064) were marginally different at alpha 0.1. Meanwhile, statistically significant differences were detected in Mg at sites 1 and 3 (p < 0.001), sites 3 and 2 (p < 0.001) as well as sites 2 and 4 (p = 0.01). CEC was statistically different at sites 2 and 3 (p = 0.001) and marginally different between sites 1 and 2 (p = 0.07) as well as sites 2 and 4 (p = 0.064). With respect to total cations, statistically significant differences (p < 0.05) were detected at sites 1 and 4 (p < 0.001), sites 2 and 4 (p = 0.023) as well as sites 3 and 4 (p = 0.04). Acid saturation was statistically different at sites 2 and 3 (p < 0.001) sites 2 and 4 (p = 0.01) while marginally differences were observed at sites 1 and 3 (p = 0.045). Statistically significant differences were detected in pH between site 4 and all other sites (p < 0.05) while N was statistically different between sites 1 and 2 (p = 0.03 and site 1 and 3 (p = 0.04). Finally, with respect to Zn, site 3 differed significantly with other sites (p < 0.001).

Table 2.4 Effects of the site factor on soil variables. Entries in bold are statistical significant (p < 0.05) and light entries are marginal significant (p < 0.1)

Soil variable	df	*F*-statistic	p-value
Bulk density (g mL^{-1})	3	4.2	**0.01**
P (mg L^{-1})	3	4.3	**0.01**
K (mg L^{-1})	3	2.2	0.09
Ca (mg L^{-1})	3	4	**0.01**
Mg (mg L^{-1})	3	11.4	**< 0.001**
CEC (cmol L^{-1})	3	5.8	**< 0.001**
Total cations (cmol L^{-1})	3	8.2	**< 0.001**
Acid saturation (%)	3	7.8	**< 0.001**
pH (KCl)	3	10.6	**< 0.001**
Zn (mg L^{-1})	3	23.2	**<0.001**
N (kg ha^{-1})	3	3.4	**0.02**

Interactive effects of site and invasion status

The interactive effects of site and invasion status had significant impact on most the analysed soil variables ($p < 0.05$, Table 2.5) except for bulk density.

Table 2.5 Interactive effects of site and invasion status on selected soil variables

Soil variable	df	*F*-statistic	p-value
Bulk density (g mL^{-1})	6	1.1	0.37
P (mg L^{-1})	6	2.4	0.042
K (mg L^{-1})	6	5	< 0.001
Ca (mg L^{-1})	6	3.5	0.01
Mg (mg L^{-1})	6	3.5	0.01
CEC (cmol L^{-1})	6	7.8	<0.001
Total cations (c mol L^{-1})	6	10.8	< 0.001
Acid saturation (%)	6	4.4	0.001
pH (KCl)	6	6.874	<0.001
Zn (mg L^{-1})	6	3.939	0.002
N (kg ha^{-1})	6	6.121	<0.001

PCA

The null hypothesis that variables were uncorrelated was rejected (Bartlett's test of sphericity, $df = 55$, $p < 0.001$). PCA was then performed and the first three axes of PCA explained 75% of the total variation. An investigation of the communalities table revealed that the factor solution extracted much of variation in the variables since they were high (0.55 – 0.95). The first rotated component had high loadings for K, Ca, Mg, total cations and acid saturation. However, it was negatively correlated to acid saturation. The second component matrix was highly positively correlated to P as well as CEC and negatively correlated to pH. The third component increased with an increase in bulk density and it was negatively correlated with Zn. In order to further illuminate on the effects of invasion status on the selected soil variables a biplot is presented (Figure 2.12). The biplot shows that most of the uninvaded sites were highly positively correlated with soil pH while the opposite vector was dominated by invaded and cleared sites (Figure 2.12). These invaded and cleared sites had higher bulk density (D), CEC, P and acid saturation compared to the uninvaded sites. At the same time one vector indicates that cleared and invaded sites were highly correlated to Mg, Ca, K, N, Zn and total cations (Total) while the opposite vector also had a huge presence of similar cleared and invaded sites. Overall, the above two vectors of the biplot were dominated by uninvaded and cleared sites with below average concentration of most of the analysed soil variables. However, pH was the only analysed variable that was higher in the two upper vectors compared to the lower panels of the biplot (Figure 2.12).

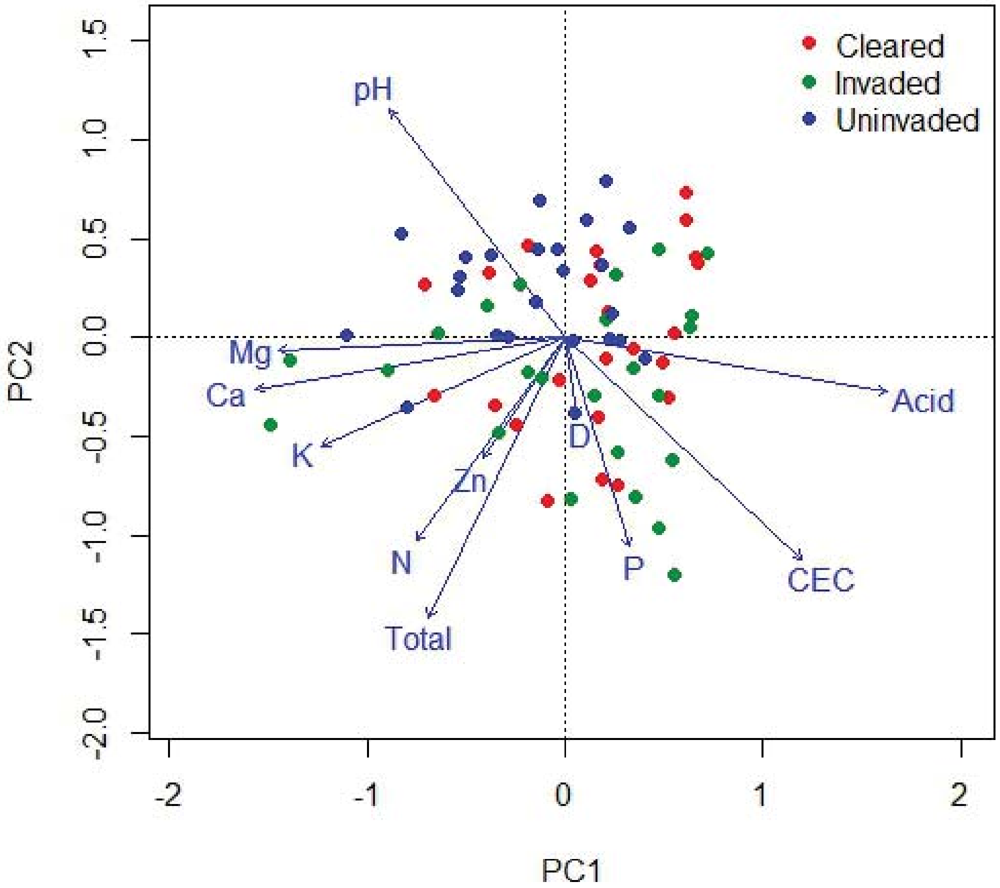


Figure 2.13 Biplot showing the first two principal components (D - bulk density, Total – total cations and Acid - acid saturation). Symbols represent the samples grouped according to the invasion status (red = cleared, green = invaded and blue = uninvaded).

2.4.3 Discussion

Response of soil attributes

The study sought to determine the impact of *A. mearnsii* on grass production by assessing selected abiotic soil properties and predicting grass ANPP in areas cleared of *A. mearnsii*. It was found that A*. mearnsii* highly affected most of the analysed soil variables. Soil characteristics are crucial in managing grasslands undergoing change from IAPs since soils are a substrate for forage production. With respect to soil chemical characteristics pH, CEC, total cations and acid saturation were analysed. Soil pH is important in rehabilitation studies since plants or forage tolerate specific pH thresholds. Although soils in the study site were generally acidic, statistically significant differences in pH were detected between cleared sites and uninvaded as well as invaded and uninvaded sites, indicating that the invasion by *A. mearnsii* altered the soil pH. This was consistent with many studies that have reported soil acidification as a result of wattle invasion (van der Waal 2009; Moyo and Fatunbi 2010; González-Muñoz et al. 2012; Lazzaro et al. 2014). The invasion status impacted significantly on soil properties related to P, CEC, total cations, acid saturation and pH. Soil chemical properties related to pH greatly influenced CEC, total cations and acid saturation. When pH is low, more exchangeable cations are acidic leading to higher acid saturation and an increase in total cations. The soil acidification has implications on the ability of forage recovery after the removal of *A. mearnsii* from the rangelands. Soil fertility is strongly coupled with the ability of a soil to retain and exchange nutrients. The ability of the soil to attract positive cations (for example, Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) was enhanced after the invasion due to increases in CEC and total cations, suggesting that these nutrients could have become more available for production. Soils with high CEC tend to attract more positive exchangeable cations indicating high clay content (Saidi 2012). Although an increase in CEC was noted, the observed values were still relatively low, suggesting that the soils had a generally higher sand content and nutrient leaching was a distinct possibility (Aprile and Lorandi 2012). Such soils require less lime to correct the pH than those with CEC values greater than 6 cmol L^{-1} (Edmeades 1982; Anderson et al. 2013; Portmess et al. 2014). It will be prudent to conduct a trial to establish lime requirements per hectare for the areas cleared of *A. mearnsii* in north Eastern Cape if active restoration of the rangelands is considered. The N content was significantly different between the invaded and uninvaded sites since it is well-established that *A. mearnsii* fixes atmospheric nitrogen and this is was consistent with results from elsewhere (Forrester et al. 2007; Moyo and Fatunbi 2010; Tye and Drake 2012; Lazzaro et al. 2014). Other growth variables (P, K and Mg) were also statistical different between the invaded and invaded areas and a similar pattern was observed in the Eastern Kouga Mountains, Eastern Cape (van der Waal 2009). This suggests that once the *A. mearnsii* is removed, more nutrients will be available to drive grass/ herbage biomass production. Notwithstanding reactions with other minerals like P, micronutrients may not be limiting at the study sites as it is well-established that such micronutrients as zinc become less soluble as pH increases and becomes greater than 6.5 (Zhu et al. 2001). The pH in the study sites was low (< 4) and hence promote the solubility of zinc.

Influence of interactive effects of site factor and invasion status

Results revealed huge variations in selected soil abiotic factors across environmental gradient in response to the invasion of *A. mearnsii*. Both the site and interactive effects of site and invasion status contributed significantly to variations in soil variables. Hence, any rangeland management intervention in complex SES described in this work should be informed by an appreciation of local soil physico-chemical properties. Admittedly, impacts of *Acacia* invasions are well documented (for example, Moyo and Fatunbi 2010; Boudiaf et al. 2013; Souza-Alonso et al. 2013; Lazzaro et al. 2014). However, it may be imprudent to prescribe similar soil management efforts in all areas. Results suggest that background soil characteristics influence the extent to which abiotic soil characteristics are transformed by *A. mearnsii*. A better understanding of local factors will give insights into an appropriate package for successful rehabilitation where active interventions are considered. Therefore, when planning active rehabilitation, it is crucial to understand background local soil characteristics and how they could interact with effects of invasion or clearance. This could inform the nature and character of interventions to improve the soil conditions.

The PCA was more illuminating in indicating the main soil transformation pathways as a result of *A. mearnsii* invasion or clearance. Results suggests that *A. mearnsii* essentially impacted physico-chemical soil characteristics by influencing properties related to growth, P availability and pH as well as soil physical properties (bulk density) coupled with micronutrients (Zn). The first principal component axis can conveniently be termed cations that affect growth qualities (K, Mg, N, and Ca), the second one, P dynamics (P and pH) and the third physical properties (bulk density) and micro nutrients (Zn). The second component is related to the influence of pH in dissolving inorganic P to become potentially available to plants since P is more soluble in more acidic soils (Devau et al. 2009). The high correlation of the second principal component with total cations and CEC is reflective of chemical reactions to dissolve inorganic P. With respect to the third component it is well-established that bulk density tends to increase with decreasing micronutrients (Horneck et al. 2011; Chaudhari et al. 2013) and this was consistent with results from the present study. PCA revealed a major environmental gradient along the axes as there were pronounced differences in adjacent sampling points. Results indicated the apparent clustering of sites according to invasion status, confirming that the selected soil variables had been transformed due to *A. mearnsii*. However, the simultaneous presence of sites with different invasion status could be related to the length of time lapsed after clearing. For example, the simultaneous occurrence of cleared and uninvaded sites on specific vectors of the biplot could be indicative of the rehabilitation that has occurred on the cleared sites to the extent that such sites became similar to uninvaded sites in terms of the assessed soil variables. It should be noted that IAP clearance at the study sites started circa 2005 and has been ongoing.

2.5 Clearing trial

2.5.1 Background of clearing trial

Analysis of soil samples in IAP cleared areas showed that the soils were acidic. Therefore, a clearing experiment was designed on a wattle and eucalyptus invaded farm area outside Grahamstown to assess if liming of an alien cleared area would affect the pH and promote grass growth. Clearing of the area was conducted over 2 weeks during which wattle and eucalyptus trees and other shrubs were removed (Figure 2.13).

Figure 2.14 Clearing of the invaded area was conducted using manual and electric saws during August 2017. The right image shows the cleared area.

Following clearing, the area was delineated to define 25 plots of 4.5 m x 4.5 m for application of different treatments of lime. An electric fence was erected to enclose the complete experimental area to keep cows and other animals that might intrude onto the plots.

2.5.2 Experimental design

The plots were numbered 1-25 and were assigned treatment type (A-E), based on quantity of lime applied to the plot, using a random number generator in Microsoft Excel:

- A = no lime / control
- B = 2.5 ton ha^{-1}
- C = 5 ton ha^{-1}
- D = 7.5 ton ha^{-1}
- E = 10 ton ha^{-1}

The amount of lime to be applied was estimated from Anderson et al. (2013) who states that 1-2 ton lime per acre (which equates to 2.5-4.9 ton ha^{-1}) should be applied to change soil pH with no tillage. The physical location of the plots on the landscape was as follows:

B (1)	A (2)	E (3)	C (4)	A (5)	C (6)	B (7)	E (8)	E (9)	C (10)	B (11)	D (12)	
C (13)	D (14)	A (15)	D (16)	B (17)	E (18)	A (19)	E (20)	D (21)	B (22)	C (23)	A (24)	D (25)

The experiment was run over six months, with measurements made before application of lime (BEFORE), at 3 months (INTERMEDIATE) and at the end of the experiment (END). The variables for which data was collected were as follows:

- Soil parameters determined by Dohne Agricultural Centre (BEFORE and END);
- Vegetation functional groups per replicate plot determined using Levy bridge (BEFORE, INTERMEDIATE and END);
- Estimated vegetation biomass using LAI using an AccuPAR Ceptometer model LP-80 PAR/LAI (Decagon Devices, Pullman, WA, USA). and DPM (INTERMEDIATE and END);
- Actual vegetation biomass (END only);
- NDVI measurements (BEFORE and END) conducted by Terreco Aviation (http://terrecoaviation.co.za/) using a MicaSense Red Edge Multispectral camera which captures data with resolution of 8 cm per pixel.

Number of Levy bridges required for vegetation functional groups per plot

A Levy bridge was used to determine the vegetation functional diversity of the treatment plots. Each sample point on the Levy bridge was classified into one of eight functional group categories: bare soil, litter, forb/fern, creeper grass, upright broadleaf, prostrate broadleaf, indigenous shrub, alien shrub.

Before the start of the experiment, 50 throws of the Levy bridge (with 10 data points per throw; Figure 2.14) were used to calculate the number of throws needed per plot to account for the variability in the vegetation cover for the experimental area. The cumulative running average of randomised data for the vegetation cover per bridge throw (sum of points where forb/fern, creeper grass, upright broadleaf, prostrate broadleaf, indigenous shrub, alien shrub were present) was plotted (Figure 2.15). The logarithmic trend line for the running average showed that 15 bridge throws were sufficient to capture a plot's vegetation cover variation.

Figure 2.15 Measuring vegetation functional groups at the start of the experiment

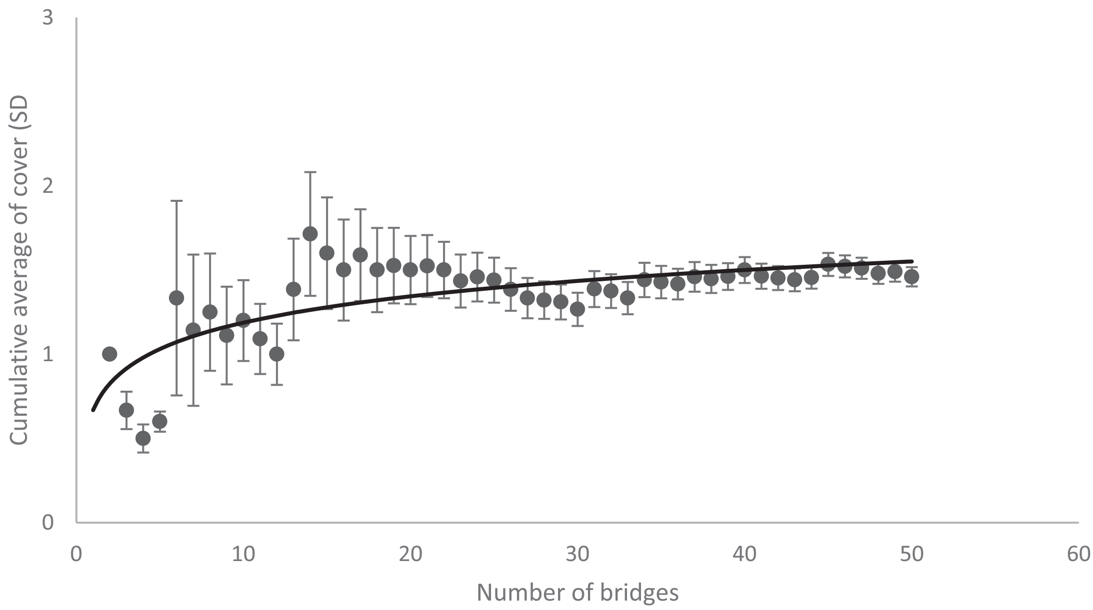


Figure 2.16 Running average and standard deviation of number of vegetation samples measured calculated using randomised bridge throws

Following the BEFORE measurements, lime was applied at 5 different treatment levels (A-E) with 5 replicates each per treatment (Figure 2.16).

Figure 2.17 Lime application on 28 September 2017

2.5.3 Results

Soil measurements

Thirteen soil samples for BEFORE treatment were collected along the length of the experimental area to determine the variation in the area (Figure 2.17). The results of the pre-treatment soil samples (Table 2.6) indicated that the soil was acidic, with significant variation in pH (between 3.85 and 5.33). The P, Ca and Mg also varied significantly across the experimental plots. However, Figure 2.18 indicates that this variation was spread across the treatments (A-E) and that the pre-treatment plots had comparable average values for the soil variables.

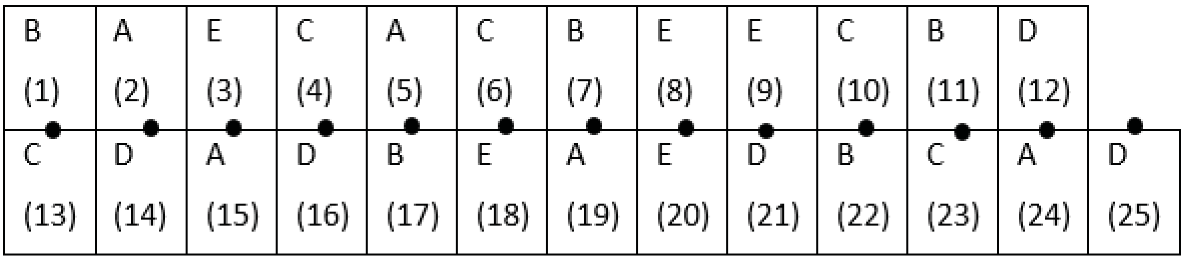


Figure 2.18 Location of pre-treatment samples relative to the experimental plots that were assigned the treatments (A-E) indicated

Table 2.6 Pre-treatment samples along the length of the experimental area (as shown in Figure 2.17) to evaluate the starting condition of the soil variables in the experimental area

Sample	pH	P (mg/L)	Ca (mg/L)	Mg (mg/L)
1	4.73	10	1445	236
2	5.2	6	1954	271
3	4.45	6	1508	271
4	3.93	5	966	224
5	4.4	6	1389	258
6	4.52	4	1234	204
7	4.23	4	1182	243
8	5.33	5	2566	333
9	5.19	7	2427	323
10	4.73	3	1775	260
11	3.85	8	958	209
12	4.06	6	1203	230
13	4.73	10	1445	236
Median	4.52	4.52	4.52	4.52
Min	3.85	3.85	3.85	3.85
max	5.33	10	2566	333

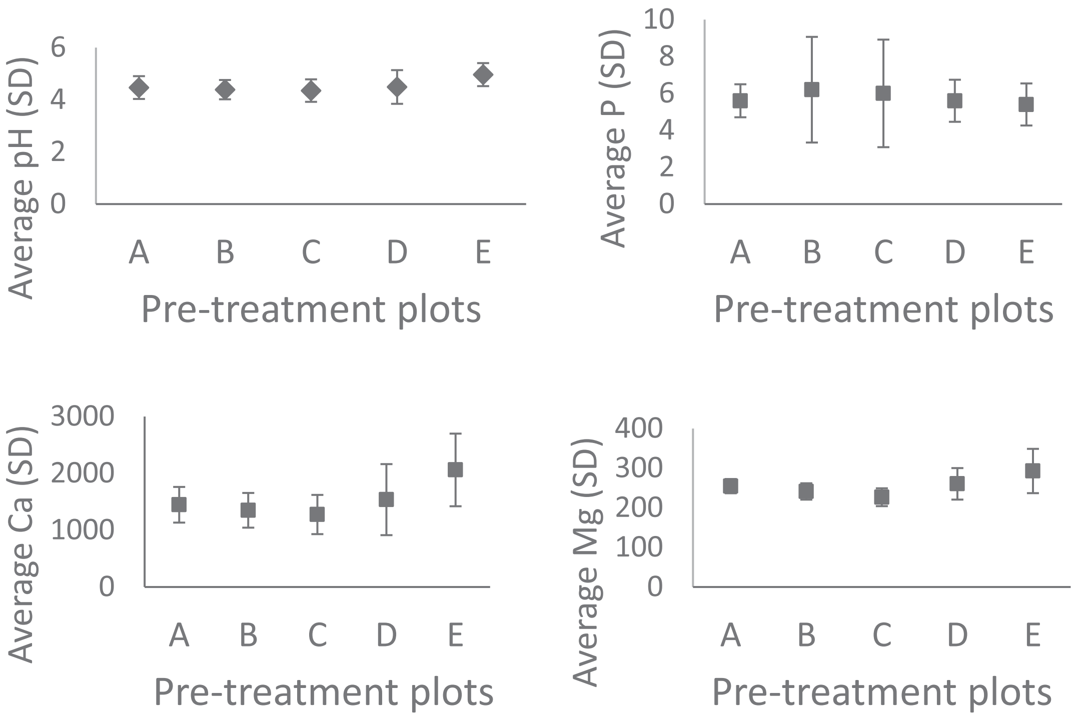


Figure 2.19 Average and standard deviation of (a) pH and elemental composition of soil samples (P, Ca, Mg) in the pre-treatment plots across the 5 treatment categories (A-E)

At the end of the experiment, three replicate soil samples were taken per plot (Figure 2.19) for a total of 75 samples. The results in Figure 2.20 indicate no difference between treatments for pH, calcium or magnesium; however, there was increase in phosphorus in the soils samples by treatment level.

Figure 2.20 (a) Collection of soil samples for pH and nutrient measurements at the end of the experiment on 18 April 2018 (left image). (b) Grass growth inside plots protected by electric fencing on 13 April 2018 (right image). Grass on the edges has been cleared to prevent grounding of the electric fence.

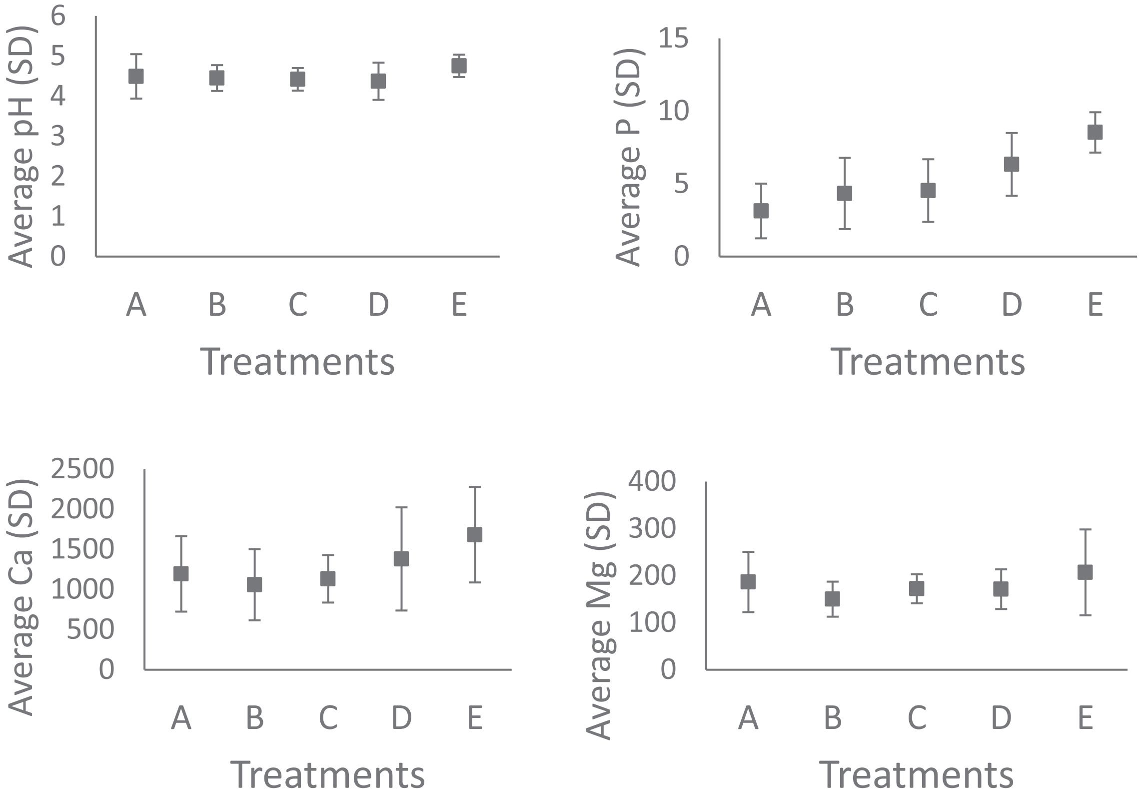


Figure 2.21 Average and standard deviation of (a) pH and (b-d) elemental composition of soil samples (P, Ca, Mg) at the end of the experiment in the plots across the 5 treatment categories (A-E)

Vegetation LAI, DPM and biomass measurements

Vegetation biomass was estimated during the experimental trial at INTERMEDIATE and END stages using LAI (4 replicates per plot; Figure 2.21) and DPM (5 replicates per plot) and the actual dry biomass (grass collected under the DPM disk; 3 replicates per plot) was determined at the END of the experiment. The relative vegetation growth in the first and second 3 months of the experiment can be seen by comparing these images.

Figure 2.22 LAI measurement on (a) 16 January 2018 (intermediate experimental stage) and (b) on 18 April 2018 (final experimental stage)

LAI results (Figure 2.22) showed a dramatic increase in LAI between the INTERMEDIATE and END stages, and although there is a trend of increased LAI with treatment level at the END of the experiment, the variation in the replicate plots is too high to see significant differences.

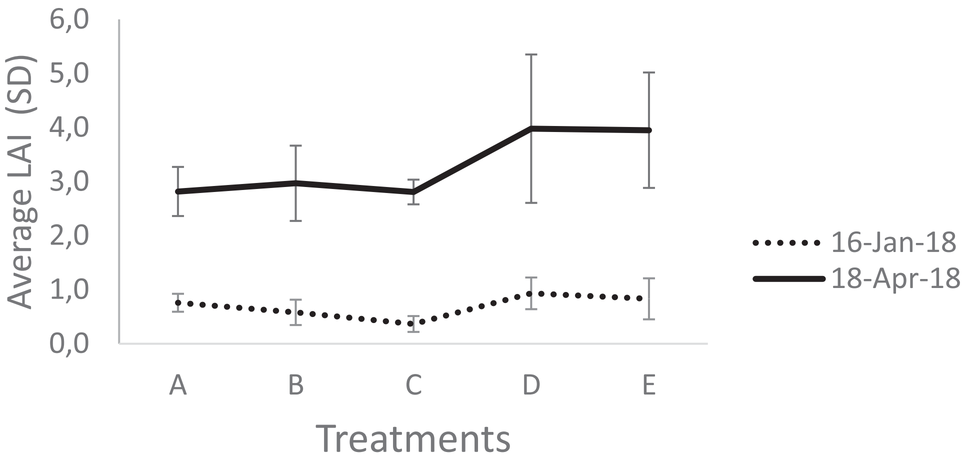


Figure 2.23 LAI of the treatment plots at intermediate and final experimental stages

DPM measurements in cm were converted to total dry biomass using the equation (Figure 2.23):

Dry mass (g m^{-2}) = 17.218 * disk height (cm) ($R^2 = 0.61$; n = 188) Equation 2.2

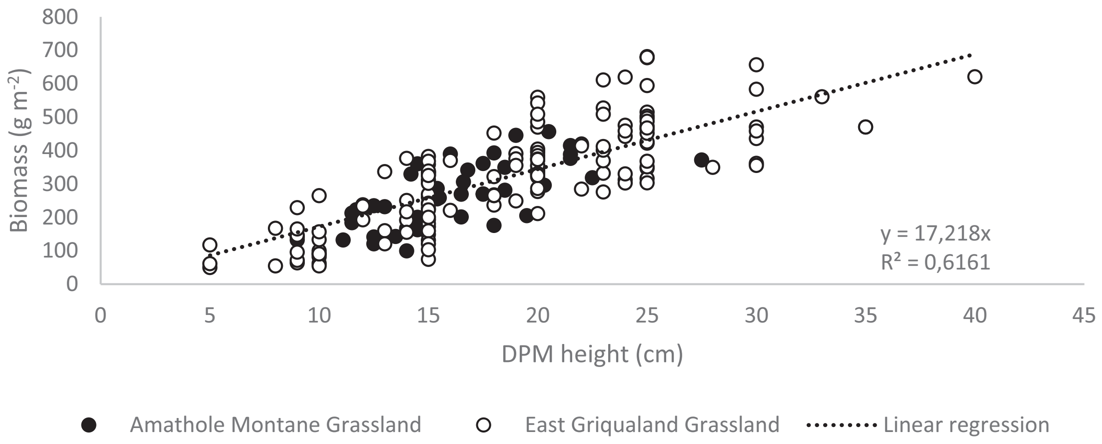


Figure 2.24 Regression of dry biomass (g m^{-2}) versus DPM height (cm) derived from unpublished data collected by Anthony Palmer and Onalenna Gwate in Eastern Cape grasslands

The results for dry mass determined by DPM and actual measurements in Figure 2.24 show over three-fold increase in biomass over the second half of the experiment, but the results are not significantly different between the treatments due to the large variation between the plots.

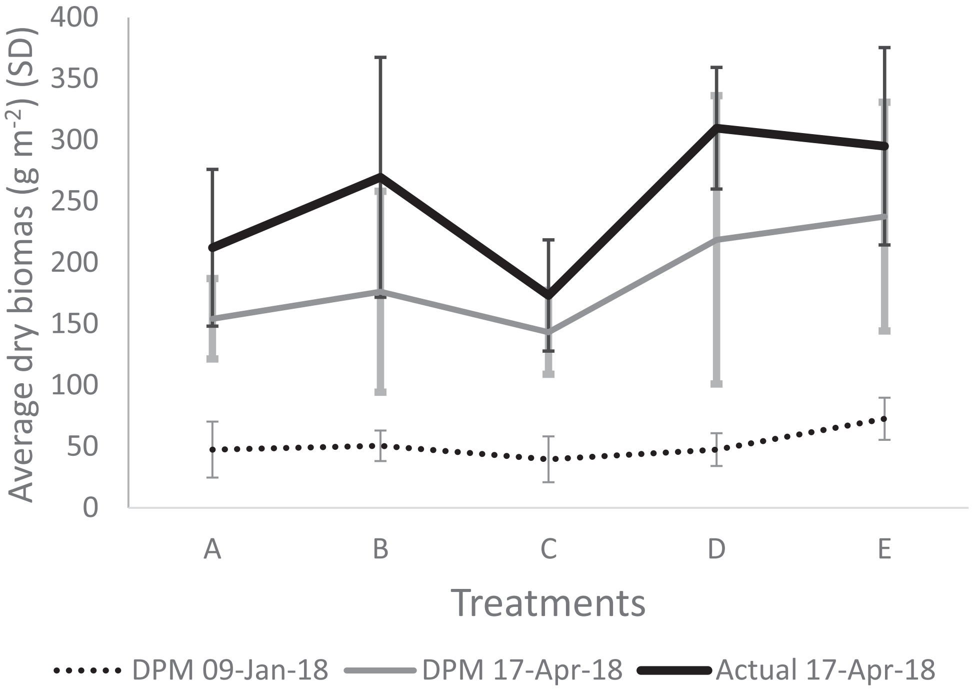
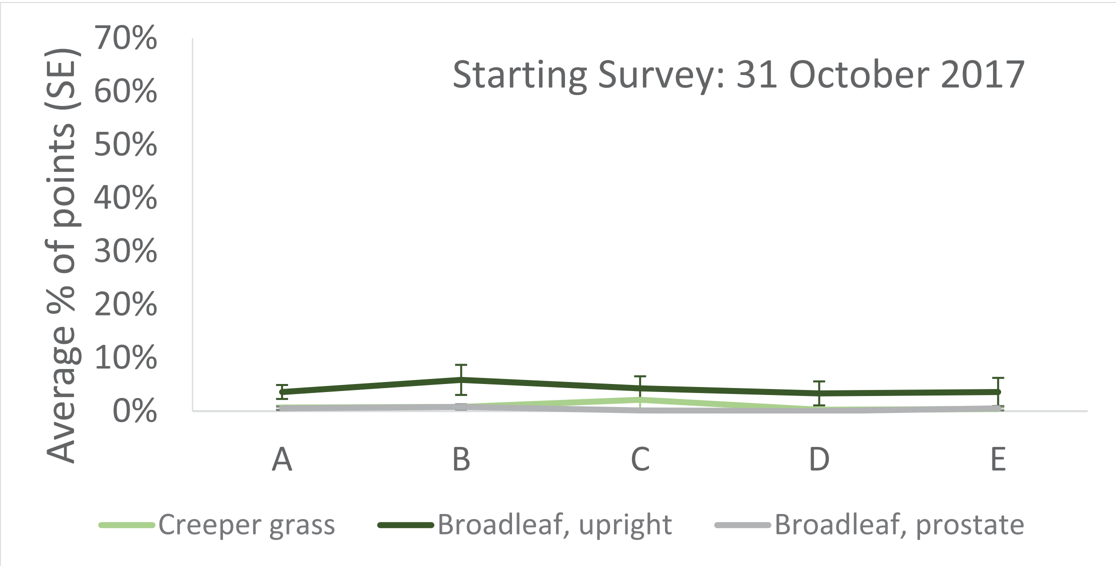


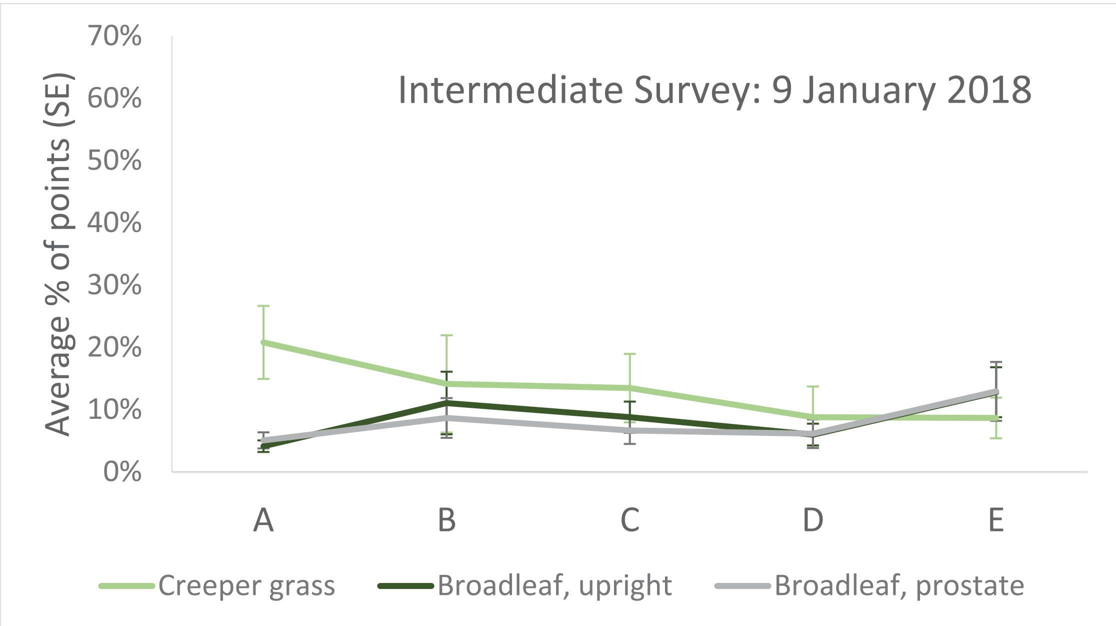
Figure 2.25 Dry biomass of grasses estimated from DPM in the treatment plots at intermediate (9 January 2018) and end experimental stages (17 April 2018) along with actual dry biomass measured at the end of the experiment

Grass functional group results

The combined cover of bare soil and litter on average was 92-95% of a plot's area at the starting stage (labelled as BEGIN). This dropped to 59-66% plot area cover by half-way through the experiment (labelled as INTERMEDIATE stage) and to 5-18% by the end of the experiment at six months (labelled END). The functional vegetation cover changed after the INTERMEDIATE stage with prostrate and upright broadleaf grasses surpassing the creeper grass cover significantly (Figure 2.25). Higher amounts of lime (treatments D and E) supported more prostrate broadleaf species over upright species in terms of area covered.

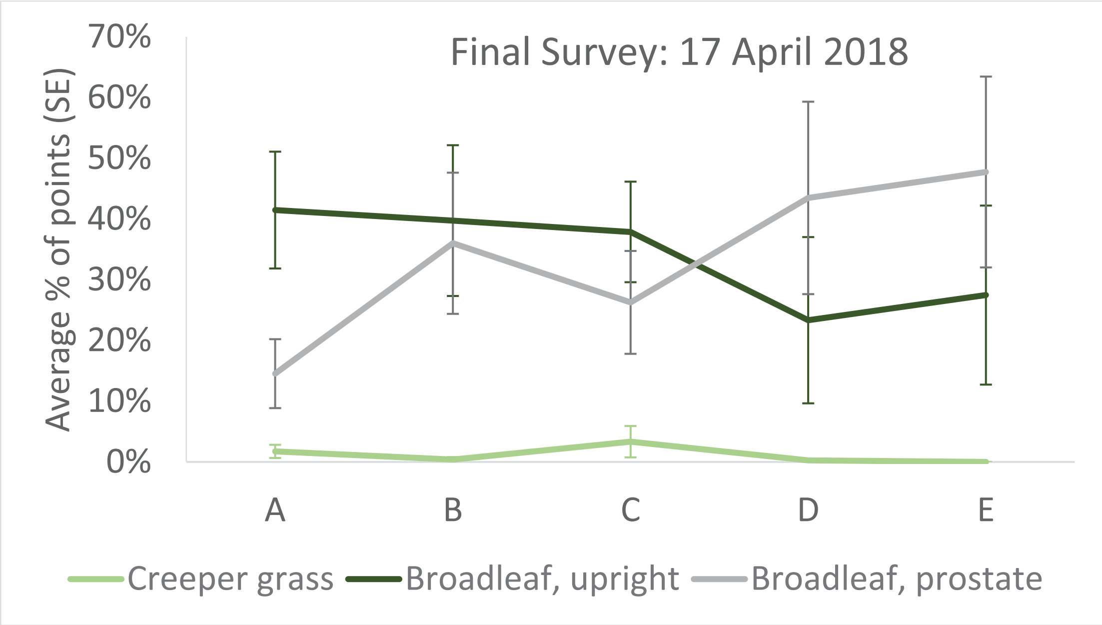


(a)



(b)

Figure 2.26 Results of vegetation functional groups survey in the treatment plots at (a) before and (b) intermediate stages of the experiment



(c)

Figure 2.27 (cont.) Results of vegetation functional groups survey in the treatment plots at (c) end stage of the experiment

NDVI measurements

(a) 

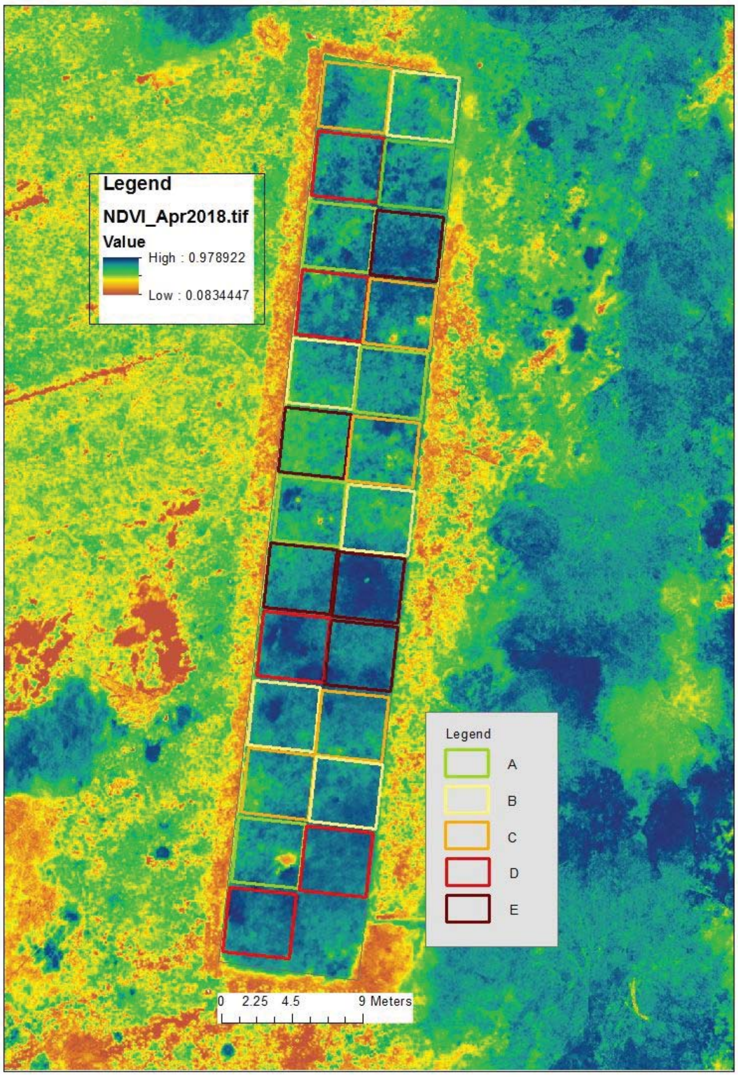
(b) 

Figure 2.28 (a) Collecting drone imagery on 13 April 2018. Note the grass growth inside the electric fence compared to outside where the cows on the farm have access. (b) NDVI data output at end of experiment. The five treatment plots are delineated with five replicates each.

NDVI data was collected at BEFORE and at END of experiment by Terreco Aviation. The exclusion of grazing resulted in significant growth in the plots irrespective of treatments as can be seen in Figure 2.26 a and b. There was significant difference in the NDVI values from BEFORE to END, but there was no difference between treatments (Figure 2.27). T-tests of NDVI data values was conducted using Statistica and results indicated treatment D and E were different than treatments A-C (Table 2.7). However, since 10 comparisons were conducted, Bonferroni adjustment should be applied with an alpha of 0.005. With this adjustment, five of the comparisons are significant (Table 2.7).

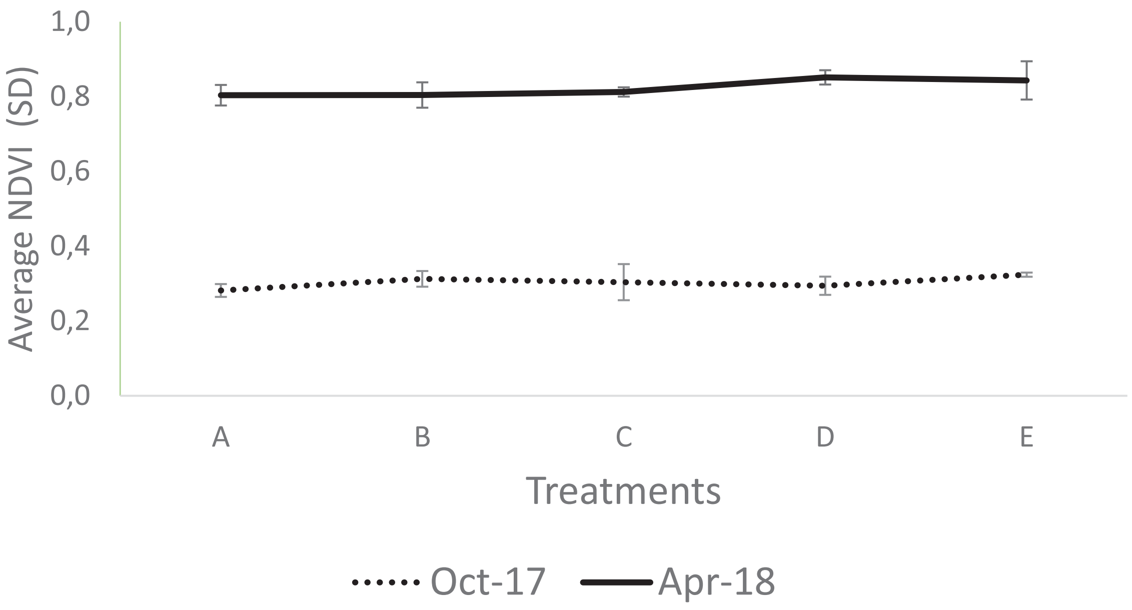


Figure 2.29 Average of 5 replicate plots with 10 NDVI point measurements per plot. Data collected by Terreco Aviation.

Table 2.7 Results of t-test analysis for NDVI data between treatments at the END of experiment. * - p<0.05, ** - p<0.005 and *** - p<0.0005; df = 98. Bold values are significant with Bonferroni adjustment.

	B	C	D	E
A	-0.04	-0.70	**-4.59*****	**-3.16****
B		-0.74	**-5.34*****	**-3.47****
C			**-4.26*****	-2.68*
D				0.86

2.5.4 Discussion

The following were the main findings of this study:

- The clearing and liming trial experiment conducted over six months showed that grasses can return in significant biomass when grazing is excluded. This supports the idea of resting being an important part of grassland management.
- Although the pH of the soils was not substantially changed by liming and the soils were still acidic (pH of 5) after the lime treatment, a trend of increase in phosphorus was seen across the treatment levels with the highest treatment showing approximately three times the average amount of phosphorus compared to the control.
- The LAI and biomass both increased by 2-3 times over the second half of the experiment, compared to the first half. However, the variability between the plots was substantial so that differences between treatments in soil variables, LAI and grass biomass were not detected. However, there appears to be a difference between the highest 2 treatments (D and E) and the control and lower lime treatments (A, B, C).
- The dominance of the functional groups changed with the amount of lime applied with broadleaf prostrate species surpassing in growth over the broadleaf upright group at higher lime treatments.
- The NDVI results were similar in the differences shown by LAI data with the highest two treatments being different than the control and lower two treatments.

2.6 Conclusions

This chapter comprises of five sections which deal with the results from different approaches to determining biomass production after clearing, and the effect of a soil remediation technique on grass production. The results provide evidence that supports several methods for measuring and improving grass production, including soil amelioration, reduction in post-clearing grazing pressure and thinning of wattle. The presence of wattle over many years has a profound effect on the biophysical attributes of any infected site. Under the wattle canopy, there is a significant effect on P, K, N, CEC, total cations, acid saturation and pH, as well as a dramatic reduction in light penetration. Three of the more important changes that directly affect forage production and forage quality are the increase in soil N and P, and a reduction in the pH (soils become more acidic). The increased acidity means that locally adapted grasses and other palatable plants (e.g. legumes) do not establish easily, and those species that do establish are generally less acceptable to grazers. The notion of 'sourveld' comes into play, as grass species with the lower N:C ratio dominate the grass sward, and grazing animals no longer select these more robust perennial grasses. These broad-leaved perennials then dominate the grass sward and grazing quality declines further. Immediately post-clearing, there is a release of N and P, and this attracts the grazing animal. This is exacerbated by the presence of shade-loving C3 grasses that have survived under the wattle canopy. These grasses are initially very attractive to the grazers, but are not tolerant of intensive grazing, and are rapidly replaced by the robust, hardy, unpalatable grasses. In the lime fertilization trial, we attempted to demonstrate that by excluding herbivores and applying agricultural lime in significant quantities, it would be possible to counteract these effects the wattle has on soil characteristics, while at the same time creating an environment that is favourable for the establishment of desirable, palatable grasses. The exclusion of grazers from the trial and the high lime applications were extremely successful in demonstrating the direct benefits of these two factors in the post-clearing period. A highly productive and palatable perennial grass species (e.g. *Panicum maximum)* appeared in the trial on the plots with high applications of agricultural lime, whereas there has been little or no evidence of its presence during the pre-clearing period. Although these 'resting' and high lime applications would be difficult to apply over large areas, we believe this approach needs serious consideration in areas where a continuous wattle canopy has been clear-felled. Exclusion of grazers need only be done temporarily and can be effected by means of a temporary electric fence, and the lime can be broadcast by hand.

In situations where there is continuous grazing of the grass sward, which occurs under most communal management scenarios in southern Africa, it is difficult to determine actual grass production as the grazing animal is continuously removing the new growth. This study has shown that the non-destructive approach of Flombaum and Sala (2007) provides a robust framework for establishing benchmark grazing capacity norms for these communal rangelands.

In the mixed farming system that was studied, livestock production is a key attribute of household food and livelihood security. By identifying the various production domains, and assessing their relative contribution to grass production, we are now able to recommend where appropriate interventions should be applied to achieve enhance livestock production. This, when combined with improved market access, will greatly enhance the household income from both sheep and cattle, which are the main livestock-based livelihood strategies. There have already been several initiatives within the project to stimulate livestock owners to participate in the developing value-chain market for natural beef products, and these should now be further encouraged.

CHAPTER 3 PARAMETERIZING, EVALUATING AND MODIFYING SUITABLE MODELS FOR EVAPOTRANSPIRATION, LWP AND NPP ESTIMATES FOR IAPS AND GRASSLANDS

by

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3.1 Introduction

This chapter addresses Aim 1 of the project, i.e. the models used in this research project to quantify actual evapotranspiration (AET), LWP and NPP for IAPs and grasslands. Section 3.2 describes the ET models used in this research, highlights sensitivities and uncertainties in ET modelling and presents some results. This work appears in several peer-reviewed publications (Palmer et al. 2017; Gwate et al. 2018a; Gwate et al. 2018b; Gwate et al. 2018c) and the reader can access the papers for further information. Chapter 3.3 addresses LWP and the model used to assess this for three different wealth groups. Finally, NPP for IAPs and grasslands is discussed in Chapter 3.4 and further information can be found in the documents published on this part of the research (Scorer et al. 2018; Palmer et al. 2017).

3.2 ET

3.2.1 Introduction

Most water management institutions, as reported in the literature on IWRM, tend to focus on blue water (water flowing in rivers, dams and groundwater) and neglect green water which is used in biomass production and ET (Rockstrom and Gordon 2001; Gordon et al. 2003). ET consists of transpiration, direct evaporation from the soil and of intercepted water. Many parts of the world are either experiencing water scarcity or will experience it shortly. In the context of global environmental changes associated with water scarcity, Hoff et al. (2010) report that IWRM with a focus on blue water only is no longer tenable and may not offer sustainable solutions. It is well-established that globally over two-thirds of the total precipitation over the continents is returned to the atmosphere as ET (Fisher et al. 2005; Mu et al. 2011; Hoff et al. 2010; McMahon et al. 2013; Liou and Kar 2014) which makes ET very important in catchment water balance. Despite this, much effort to increase water availability for agriculture has been directed through adding blue water in the form of irrigation and ignoring the need to manage the green water component (Jewitt 2006). At the same time it is envisaged that in future green water use will increase given that many regions of the world have utilised blue water resources to the limit and so improving green water management will be critical in enhancing global production systems (Hoff et al. 2010; Liu and Yang 2010). Hence, tapping into the potential of green water through enhancing water productivity (WP), the so-called "more crops for less drops" approach, could be critical in providing additional water for human sustenance (Molden et al. 2010). Therefore, parameterising ET models at the scale of land cover could be an important starting point towards improved green water management.

During photosynthesis, plants accumulate new biomass as they release water in exchange for atmospheric CO_2. For vegetated land surfaces, ET rates are closely related to the carbon assimilation rates of plants (Franks et al. 2013). Therefore, improved understanding of such ecohydrological dynamics is crucial if the scientific community is to address landscape change resulting from climate and land use changes. It is well-established that the density, size and dynamic properties of stomata determine stomatal conductance which in turn influences the rate of exchange of carbon dioxide for water vapour at the leaf surface (Schulze et al. 1994). Meanwhile, exposing plants to elevated [CO_2] induces a change in leaf anatomy through changes in stomata aperture and a decrease in stomatal density (Woodward and Kelly 1995; Franks et al. 2013). At the same time, vegetation reduces stomatal conductance at higher [CO_2] and conversely under reduced concentrations, plants increase stomatal conductance (Gedney et al. 2006; Medlyn et al. 2011; Héroult et al. 2013). Consequently, this affects the nature and character of vapour exchanges between the leaf and its environment as plants adjust to control stomatal conductance to CO_2 and water vapour to a value that will optimise carbon gain with respect to water loss (Franks et al. 2013).

Although, much of ET modelling is based on the classical works of Thornthwaite, Priestley and Taylor, and Penman-Monteith, the latter is more theoretically robust (Moran et al. 1996; Cleugh et al. 2007; Fisher et al. 2008; Leuning et al. 2008). In addition, the PM approach is driven by readily available meteorological data and it requires few parameters. However, it should be recognised that no single model may do better than all other models under all circumstances (Overgaard et al. 2006).

Land surface ET is one of the least understood and difficult to measure ecohydrological process. Consequently, a number of approaches have been developed to either measure or model it. ET measurement instruments include the Bowen ratio, EC systems, surface layer scintillometers, lysimeters and soil water balance approach (Li et al. 2009). However, these classic methods of ET determination tend to be point samples, costly, time consuming, labour intensive and sometimes subject to instrument failure (Courault, Seguin and Olioso 2005; Li et al. 2009; Liou and Kar 2014). On the other hand, ET modelling is based on several approaches including water balance, energy balance, temperature, and radiation models (Fisher, Whittaker and Malhi 2011). Consequently, a number of approaches have been developed to try and characterise the exchange of carbon between the land surface and the atmosphere (for example, Cleugh et al. 2007; Leuning et al. 2008; Li et al. 2009; Fisher et al. 2011; Mu et al. 2011; McMahon et al. 2013; Liou and Kar 2014). The energy balance concept and net radiation are used as the principal parameters in most of the remote sensing methods for estimating evapotranspiration (Liou and Kar 2014). Hence, integration of ancillary ground information with remote sensing imagery is often able to provide repetitive and synoptic views of crucial parameters characterising land surface interactions, surface energy fluxes, and surface soil moisture (Liou and Kar 2014).

It should be recognised that, no single model may outperform all other models in all situations and thus model selection should be based on the scale and purpose of application as well as the available data (Overgaard et al. 2006). Big leaf (single source) models are widely used because they are highly simplified and yet are physically sound (Overgaard et al. 2006). Some of these single source energy balance models that have been applied in southern Africa include the *Surface Energy Balance Algorithm for Land* (SEBAL) and Surface Energy Balance System (SEBS). Recent versions of SEBAL are strongly controlled by intellectual property restrictions and therefore not available for unaffiliated researchers, while SEBS was found inappropriate because of its sensitivity to a number of parameters (Gibson et al. 2013). Dual and multiple layer models have been proffered as alternatives to single source models and hence were presumably more robust for example, (Shuttleworth and Wallace 1985; Baldocchi and Harley 1995; Norman et al. 1995; Anderson et al. 1997; Kustas W.P. and Norman J.M. 1997; Gu et al. 1999; Yunhao et al. 2005). The PM model originally evolved as a big leaf model but a number of workers have enhanced its skill to also account for soil evaporation (Leuning et al. 2008; Morillas et al. 2013).

3.2.2 *Background of selected model*

A number of factors were considered in selecting models for the study and since the PM equation is more theoretically robust (Moran et al. 1996; Cleugh et al. 2007; Fisher et al. 2008; Leuning et al. 2008) it was selected together with the MOD16 ET model (Mu et al. 2011). The biggest challenge in the implementation of the PM equation is the need to characterise surface and stomatal resistances in order to connect PET to AET. It should be observed that the original PM evolved as a big leaf model which treats the canopy as a uniform single surface/leaf. However, in semi-arid areas characterised by patchy, short vegetation (Yunhao et al. 2005; Villagarcía et al. 2007) and climate seasonality, such an approach may not be tenable. Consequently, much recent effort on the PM equation has focused on extending it into a dual or multiple source model. The dual source models estimate ET from plants and direct soil ET, or ET from two plant types, while multi- or three-layer models estimate ET from plants, soil under plants, bare soil or even three types of plants (Villagarcía et al. 2007). ET is computed as a sum from different substrates. A number of researchers have attempted to reduce the original PM PET to AET (for example, Allen et al. 1998; Cleugh et al. 2007; Mu et al. 2007; Leuning et al. 2008; Zhang et al. 2010; Morillas et al. 2013; Palmer et al. 2015; Glenn et al. 2015). To this end, we adopt three formulations of the PM equation for this study. The first method is described by Leuning et al. (2008), Zhang et al. (2010) and Morillas et al. (2013) and is conveniently called the Penman-Monteith-Leuning (PML) equation. The second method is described by Palmer et al. (2015), conveniently called PMP equation and the third approach is the global MOD16 ET algorithm described by Mu et al. (2007, 2011, 2013).

3.2.2.1 Introduction to the PM evapotranspiration model

The classical work of Penman (1948) recognised that resistance to evaporation was determined by aerodynamic conductance over water surfaces and stomatal conductance in vegetated areas. Consequently, Penman (1948) provided a model to estimate evaporation from wet surfaces using meteorological inputs of solar radiation, humidity, temperature and wind speed:

$$\lambda E = \frac{\Delta \mathrm{A} + (\rho \mathrm{C}_p) D_a gH}{\Delta + \gamma\left(\frac{gH}{G_a}\right)} \qquad \text{Equation 3.1}$$

where λE is latent heat energy (Wm^{-2}) or evapotranspiration (mm), *gH* is the conductance of heat (W m^{2} K^{-1}), A is the available energy absorbed by the surface (W m^{-2}), i.e. net radiation (R_n) minus soil heat flux (G), γ is the psychrometric constant (kPa ^{o}C^{-1}), ρ is air density (kg m^{-3}), C_p is specific heat capacity of air (J kg^{-1} K^{-1}), Δ is the slope (s) of the curve relating saturation water vapour pressure to temperature (kPa ^{o}C^{-1}), D_a (kPa) is $e * (T_a) - e_a$which is the water VPD of the air, in which $e * (T_a)$ is the saturation water vapour pressure at air temperature and e_a is the actual water vapour pressure, G_a is aerodynamic conductance (m s^{-1}) to water vapour which is determined by wind speed. Equation 3.1 was reduced by assuming $gH = G_a$ (Penman 1948; Whitley 2011) to give the Penman equation:

$$\lambda E = \frac{\Delta \mathrm{A} + (\rho \mathrm{C}_p) D_a G_a}{\Delta + \gamma} \qquad \text{Equation 3.2}$$

Monteith (1965) changed Equation 3.2 to incorporate the biological mechanism of the stomata. This was achieved by recognising that the transfer of water vapour (gv) was via the stomata and the aerodynamic conductance ($gv = G_a + g_s$) and again assumed that $gH = G_a$ such that:

$$\gamma\left(\frac{g_H}{g_v}\right) = \gamma\left(\frac{G_a}{G_a+g_s}\right) = \gamma\left(1+\frac{G_a}{g_s}\right)$$ Equation 3.3

where g_s is the stomatal conductance and all terms have been defined.

Monteith (1965) noted that when evaporation from the soil is negligible, g_s is essentially a function of plant behaviour. Suffice to note that Monteith (1965) imagined evaporation as taking place from a single big leaf or layer. However, in situations where evaporation from the soil is comparable with transpiration, g_s becomes a bulk factor representing resistance of plant leaves and soil surface to ET expressed in this work as G_s. The combination equation for predicting ET was finally expressed as:

$$\lambda E \; = \frac{\Delta A + (\rho C_p) D_a G_a}{\Delta + \gamma\left(1+\frac{G_a}{G_s}\right)}$$ Equation 3.4

where G_s is surface conductance accounting for evaporation from the surfaces and transpiration.

However, it is more useful to determine the contribution of the canopy and the bare surface to G_s in order to improve the understanding of energy and water vapour fluxes. Hence, the determination of G_s has been a subject of intense research (for example, Cleugh et al. 2007; Leuning et al. 2008; Mu et al. 2007, 2011; Morillas et al. 2013). The PM equation allows total evaporation to be calculated based on the ratio of G_s and G_a which represents the surface and the atmosphere coupling (Whitley 2011). In addition, the land surface is efficient in turbulent transport across the landscape. Therefore, over relatively dry surfaces ET is predominantly driven by D_a and G_s (Cleugh et al. 2007; Whitley 2011). Where $G_a >> G_s$, the flow of water vapour is a function of:

$$\lambda E \; = \frac{\rho C_p D_a G_s}{\gamma}$$ Equation 3.5

On the other hand, over moist surfaces such that $G_a << G_s$, the flow of water vapour is described by the equilibrium evaporation equation and ET is essentially a function of R_n and G_a, and may be limited only by VPD or D_a:

$$\lambda E \; = \frac{\Delta A}{\Delta + \gamma}$$ Equation 3.6

Sensitivity of the PM equation to input parameters was conducted as part of this research and is reported in Gwate et al. (2018a).

3.2.2.2 Partitioning transpiration and soil evaporation

It should be noted that G_s as initially conceived by Monteith (1965) in equation 3.4 does not partition between transpiration (*T*) and soil evaporation (E_s). This may not be useful in situations where separating E_s and T is important. In semi-arid areas that are characterised by patchy, short vegetation and climate seasonality, evaporation from the soil is critical and can account for ~ 80% of the total (Villagarcía et al. 2007; Leuning et al. 2008; Zhang et al. 2010; Morillas et al. 2013). Transpiration (*T*) is reflective of carbon accumulation through the process of photosynthesis while E_s is related to what agriculturalists refer to as 'unproductive' loss of water to the atmosphere (Hoff et al. 2010; Kool et al. 2014). In a context of increasing water scarcity coupled with global environmental changes, there is need for better quantification of various components of ET such as *T* and E_s. This may provide a good starting point for enhancing productive water use and reduce the so-called 'unproductive' evaporation to increase food production systems particularly in water-limited areas like South Africa.

Recent efforts on improving the PM equation have focused on extending it into a two or multiple layer model (for example, Allen et al. 1998; Cleugh et al. 2007; Mu et al. 2007; Leuning et al. 2008; Zhang et al. 2010; Morillas et al. 2013). Hence, in light of these changes, this research adopts the improved formulations of the PM equation in order to better characterise water vapour fluxes. The dual layer models estimate ET from plants and E_s or ET from two plant types while multiple or three-layer models estimate ET from plants, soil under plants, bare soil or even three types of plants (Villagarcía et al. 2007). ET is computed as a sum from different substrates. Figure 3.1 presents a simplified diagram to show a layer of resistances to evapotranspiration.

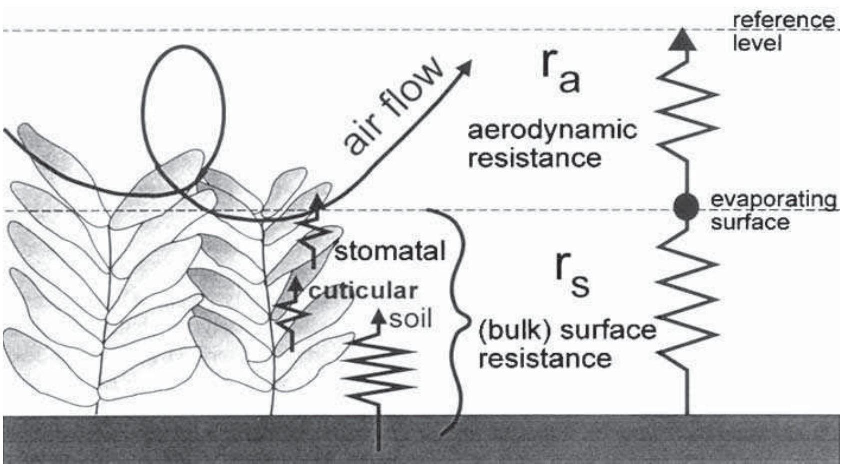

Figure 3.30 Surface and aerodynamic resistances to evapotranspiration (Allen et al. 1998)

The biggest challenge in the implementation of the PM equation is the need to parameterise canopy and surface conductance. Therefore, if surface and canopy conductance are properly parameterised, it will become easier to calculate ET for different land covers using essentially meteorological data available from sparsely distributed weather stations.

3.2.2.3 PML equation

Arguably, the PML represents a multiple source model of ET as it accounts for ET from the soil, canopy and under the canopy. As already indicated, key to the application of the PML formulation is the correct estimation of the aerodynamic resistances (canopy and soil conductance). Leuning et al. (2008) demonstrated that Equation 3.1 can be expressed as:

$$\lambda E = \frac{\varepsilon A_c + (\rho C_{p/\gamma}) D_a G_a}{\varepsilon + 1 + \frac{G_a}{G_c}} + f \frac{\varepsilon A_s}{\varepsilon + 1}$$ Equation 3.7

where the first part represents evaporation from the canopy and the second that from the soil.

A_s and A_c (M J^{-2}) are energy absorbed by the soil and canopy respectively;

G_c - Canopy conductance (m/s^{-1});

f - is a factor which modulates PET rate at the soil surface expressed by the equilibrium evaporation formulation of Priestley and Taylor (1972);

$Eeq,s = \varepsilon A_s/(\varepsilon + 1)$, with *f* = 0 when the soil is dry and *f* = 1 when the soil is completely wet (Morillas et al. 2013). *Eeq,s* is equilibrium evaporation from the soil and all other terms have been defined in Equation 3.1.

The work of Leuning et al. (2008) built on the preceding works by Cleugh et al. (2007) and Mu et al. (2007) who demonstrated that the PM formulation was a robust approach to characterising ET. Cleugh et al. (2007) compared the aerodynamic resistance–surface energy balance model and the PM methods of calculating ET and the latter provided a better estimate. They used a simple linear relationship between G_s and the remotely-sensed LAI obtained from the MODIS instrument mounted on the polar orbiting Terra satellite to calibrate G_s. Mu et al. (2007) revised the model for G_s by introducing scaling functions that ranged between 0 and 1 to account for the response of stomata to humidity deficit of the air, D_a and air temperature (T_a). They also introduced a separate term for evaporation from the soil surface. The revised G_s algorithm of Mu et al. (2007) resulted in good agreement between predictions of ET by the PM equation and the flux tower measurements. Leuning et al. (2008) modified the method of calculating surface conductance (G_s) based on the biophysical understanding of leaf and canopy level plant physiology, radiation absorption by plant canopies and evaporation from the underlying soil surface. G_s was seen as a function canopy conductance (G_c) which in turn was influenced by maximum stomatal conductance (g_{sx}) of leaves as well as energy available at the canopy and at the soil surface. Hence, Leuning et al.'s (2008) G_s formulation incorporated a drift towards a multiple source approach as the formulation incorporated bare soil evaporation, evaporation under the canopy, and transpiration. In order to parameterize G_s, Leuning et al. (2008) constrained the fraction of evaporation from the soil as a constant ranging from 0 (no soil moisture) to 1 (saturated soil) but acknowledged that *f* should be treated as a variable, especially for sparsely vegetated sites (LAI <3). The g_{sx} and *f* required to parametrise G_s were estimated using optimisation. The new Leuning et al. (2008) G_s model improved ET estimates when tested against flux tower data in different environments.

Despite Leuning et al.'s (2008) progress in calibrating G_s, the determination of the *f* value as a variable rather than a constant remained a challenge in order to account for evaporation from the soil particularly in patchy and short canopies. Pursuant to this, Zhang et al. (2010) used the ratio between precipitation and equilibrium evaporation rate as an indicator of soil water availability to obtain f values, conveniently called f_{zhang} over successive 8 day intervals. However, for arid and semi-arid zones, characterised by irregular precipitation which causes rapid increases in soil moisture during rain followed by extended drying periods, Morillas et al. (2013) postulated that f_{zhang} was inadequate. They tested three different approaches to estimate the temporal variation of *f*:

(i) using direct soil water content measurements;
(ii) application of the f_{zhang} method of Zhang et al. (2010); and
(iii) a simple model for modelling the soil drying after precipitation.

Morillas et al. (2013) found that determining the (*f*) component as a function of soil drying after precipitation (f_{zhang}) yielded better results than determining the *f* component as either a function of precipitation and equilibrium evaporation ratio (f_{zhang}) or determining it as a function of soil water content (f_{SWC}).

3.2.2.3.1 Evaluating PML Model sensitivity

Aerodynamic conductance

Preliminary analysis revealed that it was critical to accurately define the G_a in order to successfully use the PML equation since these parameters determine G_a.

suggests that the model can easily overestimate ET if the canopy height, the height of wind speed measurement and the wind speed at canopy surface are not properly defined. By increasing the height of wind speed measurement, surface resistance to evaporation decreases, leading to an increase in ET. Therefore, application of requisite wind profiling methods will be critical in the estimation of ET and Gwate et al (2018a) have demonstrated the sensitivity of PML to aerodynamic components.

Table 3.1 Model sensitivity to G_a

Canopy height (m)	Height of wind speed measurement (m)	Total ET (mm)
0.12	2.0	1158.7
0.50	2.0	1025.6
0.50*	2.0	572.3
0.50**	0.5	451.7

* wind speed at 2 m was extrapolated to wind speed at 0.5 m (canopy height) using the power law and height of wind measurement was maintained at 2 m.

** wind speed at 2 m was extrapolated to wind speed at 0.5 m (using the power law) and canopy height (0.5 m).

LAI and soil evaporation

Furthermore, sensitivity analysis has shown the importance of LAI in partitioning ET between ET_s and ET_c The analysis showed that at low LAI values ET_s is higher than ET_c (Table 3.2).

Table 3.2 Model sensitivity to LAI

LAI	ET_s	ET_c	Total ET	Percentage ET_s
1.0	446.1	124.5	570.0	78
2.0	277.6	318.1	595.7	47
2.5	214.0	403.8	618.0	35
3.0	162.2	476.9	639.1	25
3.5	121.8	537.2	659.1	19

This suggests the need for accurate estimates of soil evaporation in a context where rainfall is received almost throughout the year and effective rainfall is about 1.65 mm.

Albedo

Albedo is another important input into the PML model and as such it has to be accurately defined. For example, preliminary analysis revealed that doubling albedo from 0.08 to 0.16 on *Acacia mearnsii* substrate results in a decrease of about 10% in total ET whilst a 15% increase in albedo from 0.35 to 0.40 results in a 10.3% decrease in ET. At the same time an increase of 15% in albedo from 0.30 to 0.35 results in a decrease of 9.2% in ET (Table 3.3).

Table 3.3 Sensitivity of PML to albedo

Albedo	ET
0.08	597.5
0.16	537.7
0.20	507.8
0.23	485.3
0.27	455.0
0.30	431.7
0.35	392.7
0.40	352.0

3.2.2.4 PMP model

This model uses LAI to scale PET to actual ET (AET). Vegetation evolution demonstrates some form of convergent evolution in terms of traits, functionality and strategies across biomes. According to the functional convergence theory (Reich et al. 1997, 2003; Zeppel 2013), plants have evolved to calibrate leaf area and light harvesting ability according to the availability of resources in order to optimise carbon fixation, such that leaf area is an objective indicator of vegetation physiological activity and plant water use. Hence, in vegetated surfaces, AET, incorporating the effect of vegetation controls on vapour fluxes in terms of bulk surface resistance, approaches PET under conditions of plentiful soil moisture availability, when plant root systems are able to supply water to the atmosphere via stomata at a rate almost corresponding to demand. However, when soil moisture becomes limiting, this relationship degrades to a fraction <1 (Allen et al. 1998; Jovanovic and Israel 2012). Following this logic, the PMP model was developed since the relationship of LAI at a time (T1) to maximum LAI (LAI_{max}), indicates the vegetation functional condition of a landscape relative to its optimum (Weideman 2013). In a similar manner this relationship can be applied to relate ET_a to *ET0*, assuming that ET0 represents the upper limit of water use possible within the system when LAI / LAI_{max} = 1. The underlying assumption is that the specific area/pixel of interest has achieved optimum growth since MOD LAI data became available, and that efficiency levels are possible to the extent that all available energy defined by the reference ET (Allen et al. 1998) is used for evapotranspiration. The PMP model is expressed as:

$$ET = \left(\frac{LAI}{LAI_{max}}\right) \text{ x } ET0 \qquad \text{Equation 3.8}$$

where LAI is the MODIS LAI for that eight-day period;

LAI_{max} is the maximum retrieved at the site over the whole data record;

ET0 is ET calculated using equation 6 in Allen et al. (1998), which is given below.

$$ET0 = \frac{0.408\Delta(R_n - \text{G}) + \gamma\frac{900}{T+273}u_2 + (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad \text{Equation 3.9}$$

where ET0 - reference evaporation (mm day^{-1})

R_n - net radiation at the crop surface (megajoules [MJ] m^{-2} day^{-1})

G - soil heat flux density (MJ m^{-2} day^{-1})

T - mean daily air temperature at 2 m height (°C)

u_2 - wind speed at 2 m height (m s^{-1})

e_s - saturation vapour pressure (kPa)

e_a - actual vapour pressure (kPa)

$e_s - e_a$ - saturation VPD (kPa)

Δ - slope of vapour pressure curve (°C^{-1})

γ- psychrometric constant (°C^{-1})

3.2.2.5 MOD16 ET algorithm

This is based on equation 3.1; however, the determination of conductances and total evaporation differs from the original PM equation and is described in Mu et al. (2011).

In summary, the MOD16 ET algorithm estimates *ET* using global daily temperature, actual vapour pressure and incoming solar radiation, and remotely-sensed LAI, fraction of absorbed photosynthetically active radiation (fPAR), albedo, and land cover type. The available energy at the land surface (R_n) is partitioned into vegetation surface and soil surface using fPAR (MODIS 15A product), assumed to be equal to canopy cover (F_c). MOD16 ET is the sum of three components:

$$ET = T_c + E_s + T_i \qquad \text{Equation 3.10}$$

where T_c, E_s and T_i are canopy transpiration (*T*), soil evaporation (*Soil E*), and interception evaporation (*Canopy E*), respectively.

For full details of the MOD16 algorithm, readers are referred to Mu et al. (2011).

3.2.2.6 Exploring uncertainty of the selected models

3.2.2.6.1 Gaps in data

Since the PML and PMP are mainly driven by meteorological data from local weather stations, accurate data is crucial for their successful implementation. Where data is missing, gap filling is required using robust methodologies. One of the recommended methods of filling meteorological data in computing ET is the method of cumulative residuals (Allen et al. 1998; Costa and Soares 2009) based on homogeneity testing and subsequent correction of inhomogeneity. The ellipse test uses the cumulative residuals from the linear regression between the candidate series (dependent variable) and data from a neighbouring station (independent variable), or the average observations of several surrounding stations inside the same climatic region. The candidate series can be considered homogeneous if the cumulative residuals are not biased. The bias hypothesis can be tested using an ellipse defining the confidence limits. Plotting the cumulative residuals against time, using the time scale (interval) of the variable under analysis, the accumulated residual curve is obtained. If all the cumulative residuals lie inside the ellipse then the hypothesis of homogeneity is not rejected for the significance level considered and the equation developed can be used to predict a meteorological parameter from a nearby related station. If the hypothesis of homogeneity cannot be accepted, then one can select the break point and the data set is divided into two subsets. Then the differences between the two regression lines are computed and finally one corrects the non-homogeneous subset portion of data set followed by regression and the developed equation is then used to fill the data. An illustration with respect to maximum temperature (T_{max}) is provided for the study site (Figure 3.31 and Figure 32).

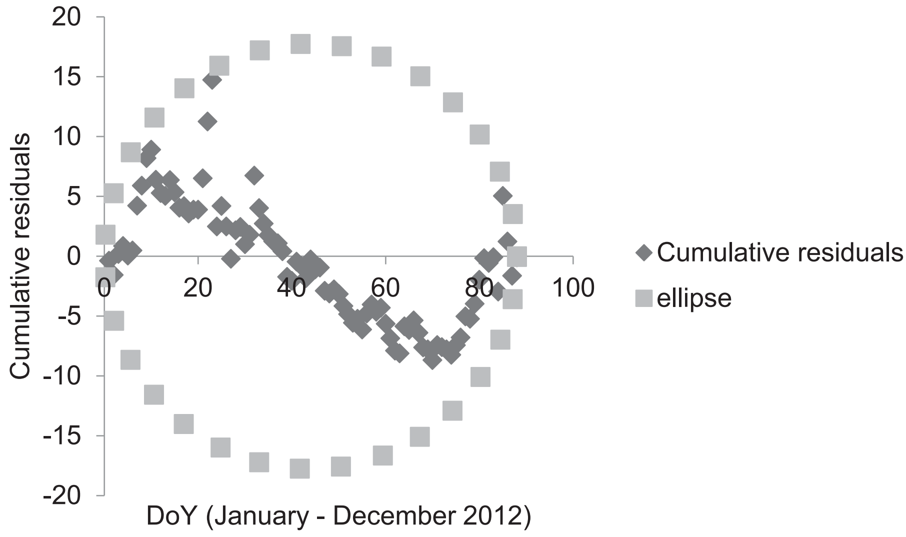

Figure 3.31 Ellipse test on maximum temperature (T_{max}).

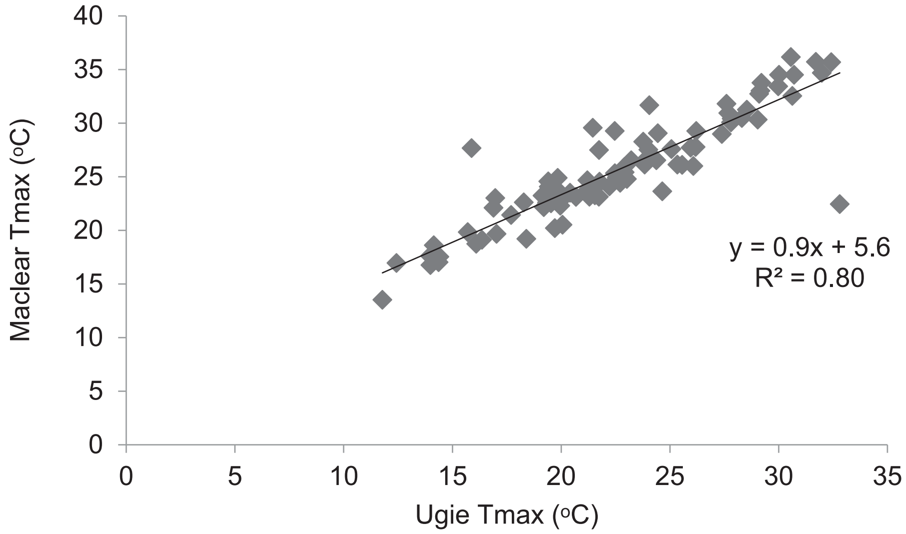

Figure 32.3 Regression equation for predicting T_{max} at Maclear (T35B quaternary)

3.2.2.6.2 Uncertainties around MODIS products

A number of researchers have described the uncertainties around MODIS products for example (Zhao et al. 2005; Mu et al. 2011; Ruhoff et al. 2013). There are essentially related to the algorithm input data from MODIS LAI product, the resampling of meteorological data from 0.05 degrees to 1 km spatial resolution and general algorithm limitations. For example, the algorithm does not account for species and vegetation stand variations and some biophysical parameters are fixed across biomes. All the selected models may suffer from some of these uncertainties since they are all driven by inputs from MOD FPAR/LAI product.

However, MODIS data has been widely used and have yielded good result comparable to measurements.

3.2.3 Materials and method

Quaternary catchment T35B (located on the Pot River within the Mzimvubu River primary catchment) was selected for model testing as in this area several important drivers are currently resulting in extensive land cover changes, including afforestation, dam construction and residential expansion. The catchment comprises several land cover classes, but is dominated by rangelands (mainly unimproved natural grasslands) that have undergone tremendous change in recent years in the form of expansion of commercial plantations and an increase in area of IAPs. Based on the land classification performed by a parallel study, main land cover types include plantations (*Pinus* and *Eucalyptus* spp.), commercial dryland cultivation, unimproved natural grasslands, wetlands and a mix of indigenous vegetation and exotic invader plants. The land tenure system within this quaternary catchment is predominantly freehold, with significant commercial forest plantations, dry land cultivation and livestock production from unimproved natural rangeland. The ET models were tested on representative cover classes that included a *Pinus* spp. plantation, a weedy *Acacia mearnsii* stand and a grassland patch cleared of several IAPs (mainly *A. mearnsii* and *Eucalyptus* spp). The cleared area was dominated by robust perennial C4 grasses (mainly *Eragrostis plana* and *E. curvula)*. The MODIS pixel resolution is 1 km^2 and the plantation covered >1 km^2. Although the cleared area and *A. mearnsii* sites covered <1 km^2, they dominated the respective sites, suggesting that the fluxes over the landscape (and thus estimated at MODIS pixel resolution) predominantly represented these land cover classes. It should be noted that it was difficult to find a large homogenous landscape when performing a study using relatively coarse resolution imagery, such as MODIS, as very few land cover classes cover contiguous areas greater than 1 km^2. It was against this backdrop that these sites were selected.

3.2.3.1 Data

3.2.3.1.1 Meteorological data

As with other PM formulations, the PML is essentially driven by meteorological data. Therefore, a number of approaches were used to derive requisite parameters from the meteorological data. Hourly meteorological data was obtained from an automatic weather station adjacent to the study site (managed by ARC) and was summarised into daily averages in order to force the PML and PMP models. The parameters included solar radiation, air temperature, wind speed, relative humidity, wind speed and rainfall. These were then used in the equations as described in this Chapter.

3.2.3.1.2 MOD15A LAI/ FPAR and MOD16 ET products

The MODIS Terra MOD15A LAI/FPAR product (V005) for the study area was retrieved from the Land Processes Distributed Active Archive Center (LPDAAC) of the National Aeronautics Space Administration available at https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod15a2. A total of 88 MOD15A (LAI/ FPAR) and MOD16 (ET) images were downloaded and batch processed using an ArcGIS model (ESRI GIS software) and registered to appropriate projection. The model iterates through all 88 images, select relevant bands, re-project to the map projection used in this project, clip images to the study area and scale the values to easily understood LAI values. The benefit of designing a model such as this is to begin automating the processing of images for ET modelling. As the project develops, more steps in the processing will be automated in a similar manner allowing for the quick processing of large and numerous spatial datasets.

Using the sample spatial analyst tool in ArcGIS version® 10.2, pixel values coinciding with the selected land cover types were extracted between day of year (DoY) 1 and 365. For each 8 day period, pixel values were extracted and filtering performed according to MODIS quality assessment (QA) flags to eliminate poor quality data. In a similar fashion to the LAI model, a model was designed in order to batch extract the QA data for each of the 88 MODIS images.

The MOD16 ET product images were accessed from the University of Maryland website www.ntsg.umt.edu/pub/MODIS/Mirror/MOD16/. Similarly, pixels coinciding with different land cover types were extracted and 8 day ET totals were computed.

3.2.3.2 ET computation

In order to explore the potential of the selected models to simulate ET trends in the study area, ET was computed using each of the models from DoY 17 to 366 of 2012. The PMP was computed following Equations 3.8 and 3.9. The computations started in DoY 17 since the PML requires the modelling to start on a day when the received precipitation is greater than effective precipitation. For our study area effective precipitation was 1.65 mm and only days 9, 12 and 13 received precipitation greater than effective precipitation. In addition, we started on this day so as to coincide with the 8 day MOD16 ET to enable comparisons. The PML and PMP compute daily ET while the MOD16 product provides an 8-day sum of ET owing to the temporal resolution of MODIS. Hence, the daily ET from PMP and PML were respectively summed up to enable comparison with the 8-day MOD16 product. It should be noted that the PML model requires g_{sx} and $\acute{\alpha}$ to be calibrated for a specific site. However, as already noted elsewhere in this report, values available in literature (Leuning et al. 2008) were used during this testing period, since we did not have enough data to calibrate these. Based on the MOD15 FPAR/LAI quality flag, only good quality LAI was used to force both the PML and the PMP models.

3.2.3.3 Correlations between models

A Reduced Major Axis regression (RMA) was performed to determine the relationship between different models. A RMA regression was found appropriate since it is suitable for data that varies and has no fixed values. It tries to minimise the squared errors in both the *x* and the *y* values.

3.2.4 Results

3.2.4.1 Acacia mearnsii

LAI data for DoY 305 and 313 of 2012 was excluded from analysis owing to poor quality. The three models had similar daily trends in ET, although the MU (MOD16 product) was generally higher than PML and PMP for the greater part of the period (Figure 3.33). The coefficients of variation were 88.3%, 74.0% and 69.7% for MU, PML and PMP respectively. The trends in ET show a dip in winter months due to reduced energy available and lower canopy cover. Suffice to note that the PML and PMP are essentially driven by LAI which also shows a similar trend. A closer look at daily ET shows that from about DoY 249 to about 297, PML was fluctuating around the MOD16 ET product. This period signals the end of winter (August) and the beginning of the growing season. As a result, ET from the soil may have been substantial since precipitation events occurred at this stage when LAI was low (0.5-0.7). Based on the PML, soil ET was 65.3 mm compared to ET from the canopy of 5.3 mm during this period. The period received about 186 mm of rainfall. Figure 3.34 shows the accumulated ET from DoY 17 to 366 of 2012. Total MU (MOD16 ET) was higher than PML ET by about 118 mm while the PMP was less than the MOD16 ET by about 278 mm during the selected period.

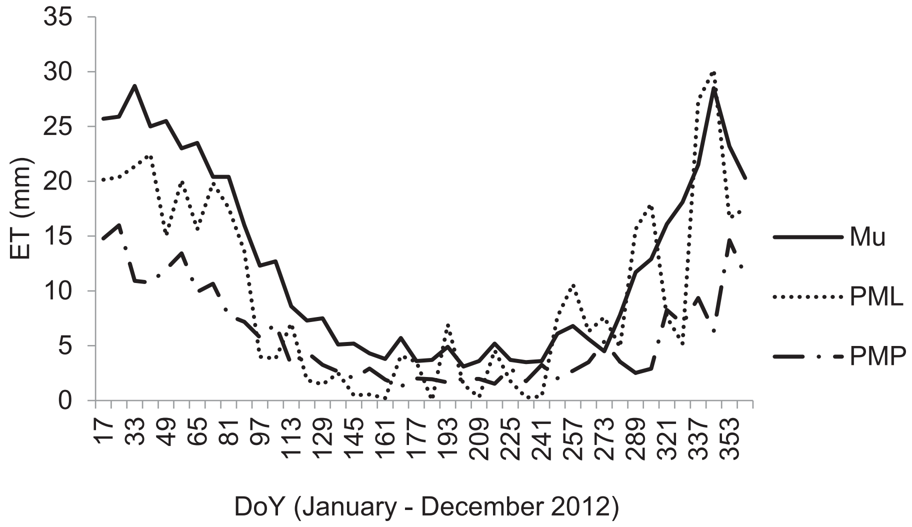

Figure 3.33 Daily *A. mearnsii* ET

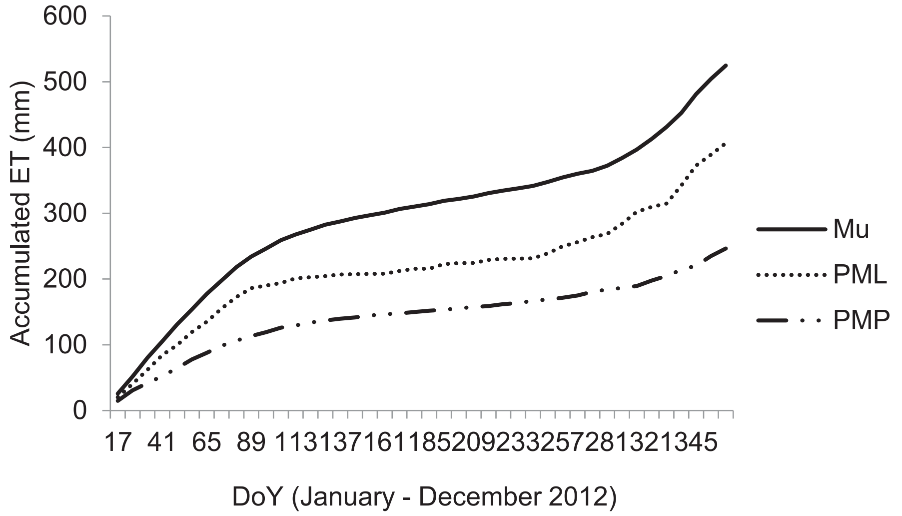

Figure 3.34 Accumulated *A. mearnsii* ET

The relationship between the three models was significant ($p<0.01$). The MOD16 ET product accounted for about 78% and 0.8% of total variation in the PML ET and PMP ET models respectively. In terms of ET totals, there was a small difference between (118 mm) the PML and MOD16ET compared to a massive difference of 278 mm with the PMP model.

3.2.4.2 Pinus spp.

DoY 337 had LAI of poor quality and thus it was excluded from the analysis. The three models had a similar daily ET trend over a pine canopy (Figure 3.35). The PMP ET was consistently lower than the other two models (Figures 3.6 and 3.7). Accumulated ET for the MOD16 ET product was 528 mm and that of PML was 386 mm while that of PMP was 259 mm. The coefficients of variation were 69.7%, 83.7% and 80% for the MU, PML and PMP models, respectively.

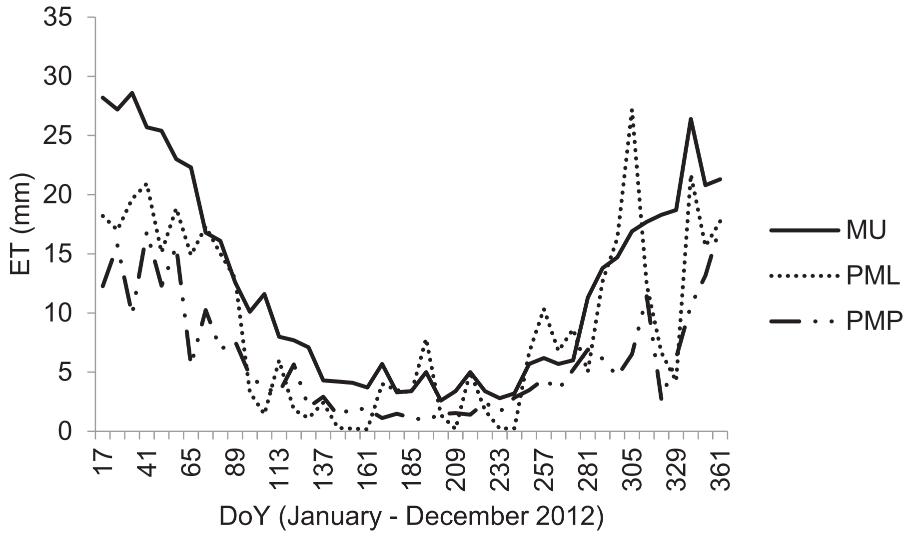

Figure 3.35 Daily *Pinus* spp. ET

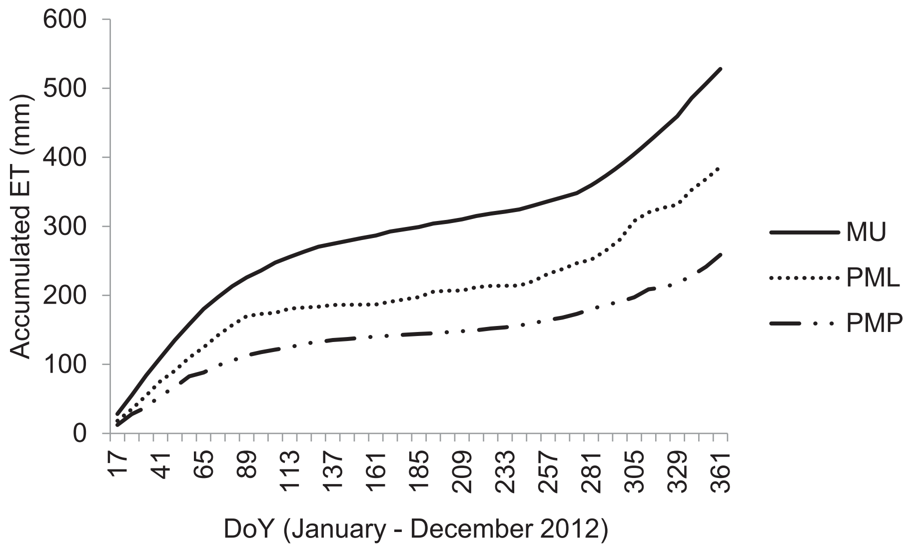

Figure 3.36 Accumulated *Pinus* spp. ET

3.2.4.3 Wetlands

According to the MOD15 product quality flag DoY 201, 217 and 289 had poor quality data and were not included in the analysis. The MOD16 ET was consistently higher than the PML up to DoY 157 and the latter oscillated around the former from DoY 249 to 313 (Figure 3.37 and Figure 3.38). Overall, the accumulated ET of the MOD16 was higher than the two other models. For example, it was higher by 288.3 mm with respect to the PMP and by 209.8 mm with respect to PML (Figure 3.38). It is also interesting to note that the accumulated ET from PML and PMP were more or less equal from day 17 to 249 over the wetland. The coefficients of variation for MU, PML and PMP were 71.0%, 85.6% and 79.8%, respectively.

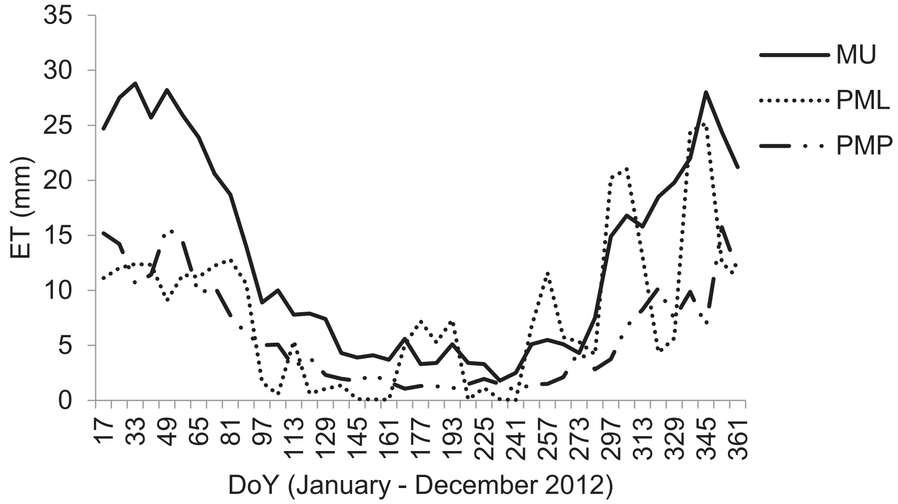

Figure 3.37 Daily wetland ET

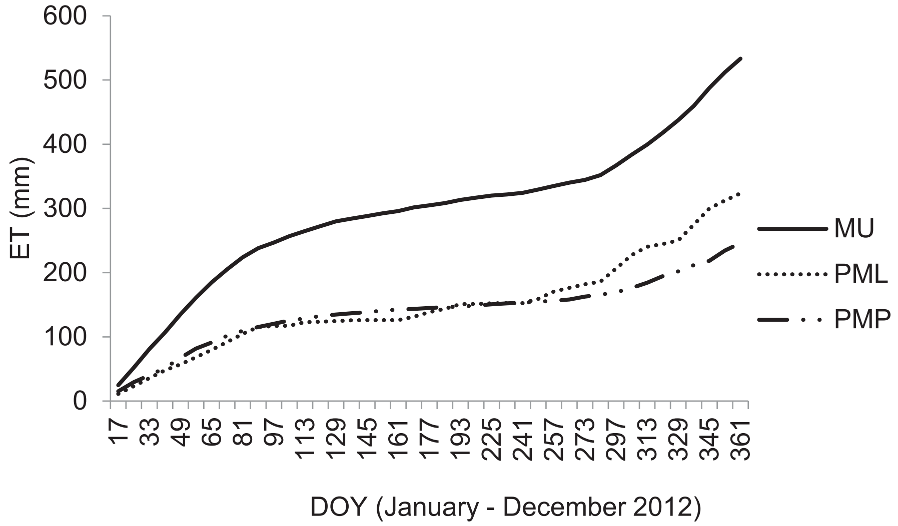

Figure 3.38 Accumulated wetland ET

3.2.4.4 Grassland canopy

Only days 225 and 313 had poor quality LAI and were excluded from the analysis. The grassland pattern of ET was similar to other cover types (Figure 3.39 and Figure 3.40). However, it is noteworthy that the accumulated PML was lower than the accumulated PMP up to DoY 305. Thereafter it started to increase through to year end. Accumulated MOD16 ET was 494.0 mm and that of PML was 351.7 mm, a difference of 142.3 mm. The total PMP ET was 151.3 mm lower than the MOD16 ET over the grass canopy. The coefficients of variation for MU, PML and PMP were 68%, 92% and 79% respectively.

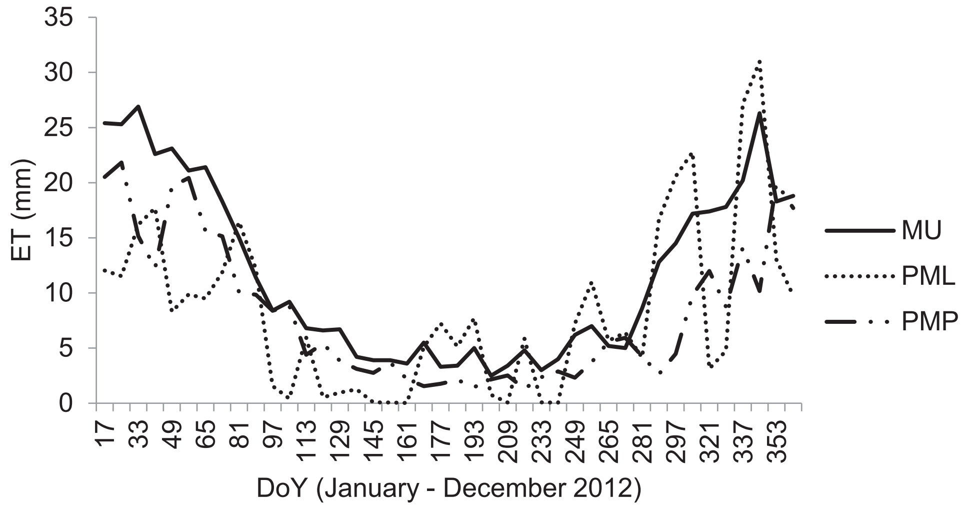

Figure 3.39 Daily grassland ET

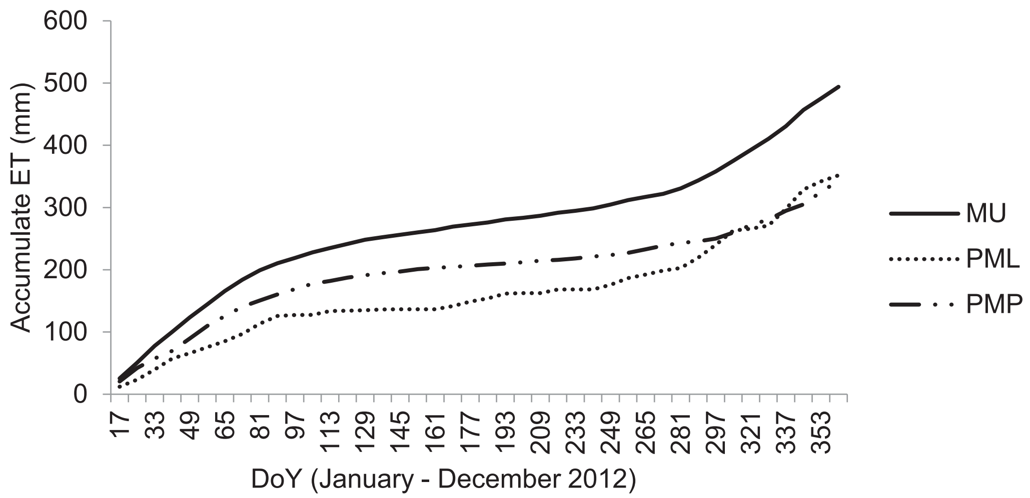

Figure 3.40 Accumulated grassland ET

3.2.4.5 Summary of accumulated ET per selected site

Table 3.4 shows accumulated ET modelled by each model for different land cover types. Across all land covers MOD16 product yielded higher ET values than other models.

Table 3.4 Accumulated ET per selected site

Land cover	Annual accumulated ET		
	MOD16	PML	PMP
A. mearnsii	524.3	406.5	246.4
Pinus spp.	528.0	386.2	258.8
Wetland	533.3	323.5	246.0
Grassland	494.0	351.7	342.7

3.3 LWP models

3.3.1 Introduction

Globally, livestock production plays a significant role in satisfying various human needs such as provision of highly nutritious food products and providing beneficial services of economic, social, cultural and ecological domains (Thomas 2000). Livestock possession may be used as a guarantee against inflation, where livestock can be converted into cash through sales from time to time (Alemayehu et al. 2012). Alemayehu et al. (2012) estimates that about 144 million people in sub-Saharan Africa that are practicing the mixed farming system and draw their livelihoods from livestock. However, because of health problems, lack of feed, capital, degradation of natural resources, low genetic potential of indigenous breeds, and limited access to improved technology, livestock productivity is generally low. Furthermore, livestock production has been widely criticized due to the negative impact it has on water resources and the environment (Descheemaeker, Amede and Haileslassie 2010). However, evidence suggests that such examples arise from industrial livestock production systems where forage and grains are produced from large amounts of water (Peden et al. 2007).

Livestock production is accountable for 20% of agricultural ET worldwide (Peden et al. 2009) and is projected to grow rapidly with increasing demand for animal products. Future agricultural water needs can be reduced through providing less water for livestock production. The water needed to grow feed is far greater than the water required by livestock for drinking which accounts for 2% of the total livestock production need (Peden et al. 2007). The feed that the animal consumes determines the physical WP of an animal product produced. Molden et al. (2007) estimates that, an amount from 3000 to 15000 litres in ET are required to produce 1 kg of animal product. The estimates vary depending on the feed type, management practices, crop residue used, processing and the ability of the animal to convert feed into animal products.

It is further estimated that, demand for livestock products increased by 6 to 8% in 2012 (Alemayehu et al. 2012). Thornton (2010) argues that the rise in income levels, urbanisation and increased population size are possible drivers to the increased demand for livestock products. According to Steinfeld et al. (2006), people tend to change their eating habits and lifestyle leading them to spending more money on livestock products as their incomes increase. Furthermore, in attempting to satisfy the changing demand for animal food products, the challenge facing agriculture is the sustainability of natural resources such as water, soil, air and biodiversity (Steinfeld 2004).

In South Africa, high livestock populations have been maintained in the communal areas which have been in significantly excess of official recommended stocking rate (Dovie, Shackleton and Witkowski 2006). This has had a long-term consequence on rangeland degradation due to the impact livestock have on communal rangeland as livestock production is perceived to be unproductive (Vetter 2013). This evidence is based on rangeland examination through looking at changes in vegetation over time and standing biomass. Destocking resulted from evidence of rangeland degradation in these communal areas from time series livestock data (McAllister 1992). Although there have been studies looking at the role and importance of communal livestock in South Africa (Cousins 1996), attention has been focused mostly on reasons for keeping livestock and their value (Shackleton et al. 2001). However, the quantification of livestock products (goods and services) and the amount of water used in producing those from communal rangelands is lacking. Furthermore, the costs associated with livestock production and the value of livestock products (goods and services) to households in a livestock production system has been lacking too.

Against this drop back, the concept of LWP can be defined as the ratio of the net beneficial good such as milk, offtake, manure, skin, hides/wool and services such as traction derived from livestock against the amount of water used by the rangeland to produce feed for grazing. (Kebebe et al. 2015). In a communal livestock production system, the concept measures the ability of livestock to convert rain water that is available into livestock goods and services which is expressed as a model/equation. The numerator of the equation represents the net beneficial outputs and their cost, while the denominator represents the amount of water used (ET) from rangelands.

As part of the study aimed at determining if communal rangelands of the north Eastern Cape can sustain maximum livestock production, LWP was described to identify areas of possible interventions to improve livestock production in communal area. Livestock products for various households in a diverse livestock production system were reported through a survey questionnaire. Information such as household demographics, household livestock holdings, net beneficial goods and services derived from livestock and their anticipated cost at the time of the study were also recorded. Further, livestock production inputs such as labour/herding availability and supplying of additional feed were also gathered. Areas where livestock are reported to be spending most of their time grazing were identified as domains where ET was calculated.

Quaternary river catchments T12A and S50E were selected for the LWP study since both are found on communal land which is traditionally administered under local Chiefs operating under similar farming systems. A farming system is a group of farms or households which have a common function and structure and are expected to produce at the same level (Haileslassie et al. 2009). The farming system may consists of mostly mixed livestock-crop farming which resulted from differences in population densities, climate, diseases, cultural practices and economic opportunities in communal areas (Ebanyat et al. 2010).

In the study area, households keep cattle, sheep, goats and poultry (Gwate 2018), with the purpose of providing meat, milk, manure, traction power, keeping them as standing assets (Cousins 1996) that can be converted in to cash at times, and for socio-cultural activities. The relative importance of different livestock species in the farming system differ. Manure fulfils a key role through nutrient cycling between and within households which enables the sustainable use of small holder plots (Garrity et al. 2012). Livestock and crops are competitive and complimentary to each other, because livestock provide traction power and organic fertilizer, while crops provide residues during the dry season (Haileslassie et al. 2009). A nuanced understanding of the nature and direction of this complementarity would be beneficial to livestock and crop intervention strategies. Traditional livestock herding in these areas has slowly gone out of favour due to mandatory schooling of young children. However, some households can afford to pay for a herder. This has been a challenge especially with fences to control the grazing of livestock falling into disrepair. Livestock are moved away from the homesteads but often come back to graze around, resulting in nutrients being transported from the landscape to the homesteads and riparian zones. Highly productive grazing (McNaughton 1985) lawns form around the homesteads and areas associated with livestock handling. It is not known what proportion of feed for livestock is derived from crop residues, but livestock and crops do compete for land and water. Households practice low-input rainfed agriculture, leading to low levels of production.

3.3.2 Method

In estimating LWP, the net value of livestock goods and services were considered in the numerator. ET, which forms the denominator of the model was calculated based on the relationship between potential ET and maximum LAI following Palmer et al. (2015).

The beneficial goods and services from livestock such as milk, manure, livestock offtake, traction and hides/wool were estimated and converted into monetary values (South African Rand [ZAR]) using the communal farm gate value. The communal farm gate value refers to the value of unprocessed animal product at the farm. In calculating these goods and services, all livestock types kept by households were included. Information on livestock herd structure, goods and services given in a year were calculated to estimate the value of these products and services as suggested (Haileslassie et al. 2009; Descheemaeker et al. 2010). The model developed in a spread sheet by Haileslassie et al.)2009) and modified by Kebebe et al. (2015) was used to estimate LWP values that were later converted in to USD. The model can be mathematically specified as follows.

$$LWP_i = \frac{\sum_{i=1}^{n}(O_i * P_i + S_i * P_i)}{\sum_{k=1}^{n} WD_k} \qquad \text{Equation 3.11}$$

where i is the unit of observation, *LWP* is livestock water productivity, O_i is the quantity of the i_{th} livestock output such as milk, offtake, hides/wool and manure. S_i is the service type such as traction of the i_{th} livestock obtained over a year. P_i is the local market price (ZAR) of the i_{th} good or service type. WD_k is the amount of water used in ET for the production of grass in the rangelands. To assess multiple benefits, one can monetise and use monetary equivalents such as rand per cubic metre of water depleted. Although non-monetary cultural benefits remain important, they are normally not included in the computation of monetised benefits of livestock.

3.3.2.1 Calculation of net value of livestock goods and services

Livestock form a vital component of agriculture worldwide. They also provide ecosystem service output and have cultural values (Haileslassie et al. 2009). However, in this study only offtake/meat, milk, manure, skin, hides, wool and traction were considered. To quantify these outputs, total livestock production of each household was estimated through a survey questionnaire administered in 2015/2016. The socio- economic survey was conducted using a structured questionnaire through some face-to-face interviews in 2015 and 2016. Livestock and non-livestock owners were randomly selected for interviews. A total of 120 households were interviewed depending on the availability and willingness to participate in the study. The interviewed households were classified into three different wealth categories (better-off, middle and poor), where multiple criteria focused on physical ownership of key assets such as livestock holding, dwelling type and technical efficiency were used rather than precarious annual cash income (Bekele et al. 2017).

The reported livestock products in each household were converted into monetary values. The livestock holdings were converted to Tropical Livestock Unit (TLU) using a conversion factor of 0.79 for cattle, 0.1 for sheep and goats (Haileslassie et al. 2009). Livestock goods and services were estimated as follows:

Milk production: Annual milk production was estimated as a function of: number of lactating cows, lactation period and milk production in litres/day/cow in a household herd per year. The total milk produced per cow was converted in to monetary values based on the value of milk at a local farm gate price.

Offtake/meat production: livestock offtake was estimated as the proportion of animals sold or slaughtered for household consumption in a year. It was calculated by summing the values of each animal type (ZAR) that was sold for consumption or gifted in a year (Kebebe et al. 2015). Number of sold animals, stock fair sales, informal sales and cultural slaughter were also measured as reported by communal farmers (Tada et al. 2012)

Manure: Manure production was calculated using dry weight daily dung production of 3.3 kg/day/TLU and 2.4 kg/day for small ruminants for the annual average livestock holdings (Descheemaeker et al. 2010; Bekele et al. 2017). Nutrient composition was estimated based on nutrient content of 18.3 g N/kg, 4.5 g P/kg and 21.3 g K/kg on a dry weight bases (Bekele et al. 2017). Monetary equivalence of manure to artificial fertilizer was extrapolated from the nutrient contents and price of Limestone Ammonium Nitrate (28).

Traction power: Traction power was estimated based on daily hiring cost of draft animals (e.g. oxen) and number of working days/year spent ploughing and threshing in every sample household.

3.3.2.2 Evapotranspiration estimate

High value goods and services are derived from water by livestock from various sources such as water consumed by drinking and water consumed through feeding. The amount of water consumed is determined by several factors related to the animal, feed and environmental conditions (Giger-Reverdin and Gihad 1991). Direct water consumption comprises only a relatively small part of total water budget. However, livestock ranching has a significant impact on water resources at landscape scale and water shed. Soil and vegetation degradation may result from the hydrological response of pastures and rangelands, which is affected by livestock grazing. Land degradation can be severe around watering points where livestock grazing pressure and trampling on vegetation can be noticed (Descheemaeker et al. 2010). In this study, areas where most grazing is taking place during wet and dry season were identified and sub-divided into different domains (Descheemaeker et al. 2010), using a combination of Earth observations and field based boundary definition. Possible domains that were identified include unimproved grasslands (riparian zones, wattle groves and areas removed of wattle), cultivated lands and around homesteads (areas associated with livestock holding such as kraals). Domain boundaries were determined through GIS mapping techniques using remote sensing.

MODIS ET was extracted from the three identified grazing domains using a pre-processed MODIS imagery (MODIS 15A3) that were acquired from Land Processes Distributed Data Archive through GEE (Map data 2017 Google, INEGI, ORION-ME, USA). The domains were separated from each other by developing polygons on Google Earth that matched ground measurements. However, only MODIS ET from unimproved grasslands was used in this study to calculate LWP. A Java script with instructions to extract data for the entire length of the MODIS record from 2001-2017 was used for both MODIS ET. On the other hand, rainfall for the entire period (2001-2017) was also extracted was the automatic weather station at Cala.

3.3.3 Results

The mean household characteristics by wealth groups are presented in Table 3.5. Livestock beneficial outputs were not significant among different wealth groups. However, TLU were significantly different among wealth group categories. Better-off households had more livestock holdings than middle and poor households. The results revealed that, livestock production input such as the money spent on labour and buying additional feed was not significant between better-off and middle wealth households. The results further revealed that mean generated outputs from livestock were similar across wealth groups with little differences.

MODIS LAI was extracted for unimproved grasslands, cultivated lands and areas around the homesteads in the study area which was integrated into the Equation 3.13 to predict AET. However, only AET from unimproved grasslands was used to calculate LWP. Maximum LAI extracted for each domain ranged from 3.8 on *unimproved grasslands*, 4.1 on *cultivated lands* and 2.9 *around the homesteads*. The AET calculated using Equation 3.13 for the year 2016 was 270 mm for the unimproved grasslands and the value of 270 mm is used as denominator for all LWP calculations.

Table 3.5 Means of household characteristics among wealth groups

Household characteristics	Better-off (n=33)	Middle (n=33)	Poor (n=54)	RMSE
Livestock holding (TLU)	2.04[a]	1.78[b]	1.98[c]	15307.06
Expenditure (USD) (labour and additional feed)	11.58	11.59	11.45	776.45
Outputs (USD)	13.63	13.27	13.16	4528.71

Different superscripts [a,b,c] within a row represents significant differences at $P< 0.05$. TLU: Tropical livestock unit: 250 kg live weight.

Table 3.6 illustrates mean LWP obtained in the study site for the three defined income classes. There were no variations in mean LWP obtained by middle and poor household wealth groups. Better-off households obtained high LWP (0.34) followed by the middle (0.29) and poor households (0.29). Results from other similar studies conducted in Ethiopia are reported for comparison. These studies show differences in LWP obtained in different wealth groups. All these studies show a similar trend, where wealthier households obtained higher LWP compared with middle and poor, although in the case of this study the differences are not significant.

Table 3.6 Mean LWP

Household characteristics	Better-off (n=33)	Middle (n=33)	Poor (n=54)	Reference
LWP (USD m^{-3})	0.32	0.31	0.30	
LWP (USD m^{-3})	0.26[a]	0.20[b]	0.16[c]	(Kebebe et al. 2015)
LWP (USD m^{-3})	0.30[a]	0.24[b]	0.16[c]	(Bekele et al. 2017)

Different superscripts [a,b,c] within a row represents significant differences at $P< 0.05$.

Figure 3.41 shows the illustration of the total household livestock types among different wealth categories. High mean numbers of different livestock species were reported in better-off households followed by middle wealth households then poor households. Sheep comprised the highest proportion of livestock species found in the village irrespective of wealth group. The goats formed the least livestock percentage kept in the village by all the wealth group categories. The results revealed a mean sheep holding of better-off (mean=49), middle (mean=23) and poor (mean= 2) among wealth groups.

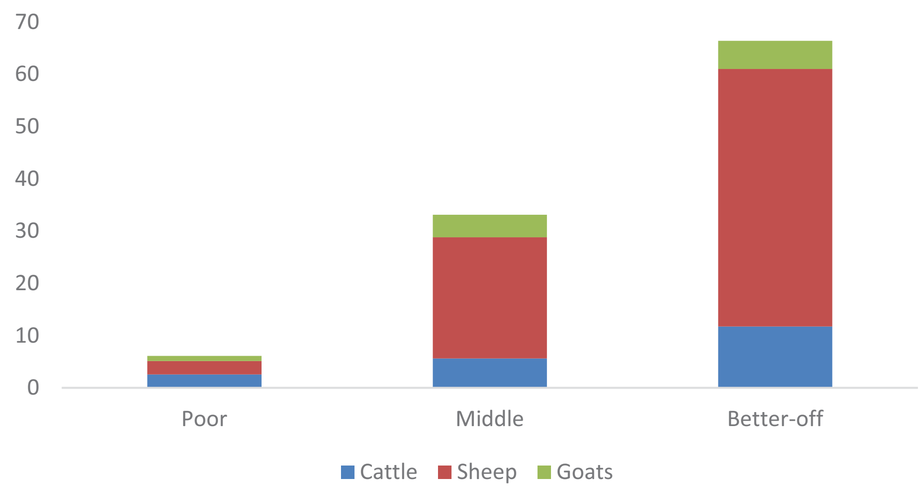

Figure 3.41 Proportion of mean livestock species among households wealth groups

The results revealed a variation in terms of individual beneficial goods and services derived from livestock by different wealth groups. However, a significant variation (Table 3.7) was reported between better- off and poor households except for wool which was similar across the three groups. Milk, offtake and traction was higher in better-off households, while middle and poor were similar. Manure production was different among the wealth groups with better-off households obtaining high manure followed by middle then poor households. Overall, significant differences in beneficial goods and services corresponded with wealth status being higher in better-off and lower on poor households.

Table 3.7 Means for livestock beneficial goods and services (USD) of households in different wealth groups

Livestock beneficial output	Better-off (n=33)	Middle (n=33)	Poor (n=54)	RMSE
Milk	7.31 ^{a}	6.24 ^{b}	6.34 ^{c}	1.31
Offtake	11.06 ^{a}	10.50 ^{b}	10.39 ^{c}	16.96
Manure	9.68 ^{a}	8.93 ^{b}	7.39 ^{c}	5.80
Hides/wool	7.73	7.57	7.45	3.31
Traction	5.22 ^{a}	4.40 ^{b}	4.82 ^{b}	08.08

Different superscripts ^{a,b,c} within a row represents significant differences at $P< 0.05$.

Figure 3.42 illustrates the contribution of annual goods and service type derived from livestock by different wealth group categories in rand value (ZAR). Irrespective of wealth status, offtake value generated the highest proportion followed by manure. In terms of South African Rands, offtake was reported to be higher in better-off (mean= R241.39) middle (mean= R173.77) and poor (mean= R182.18) households. Livestock beneficial outputs and services such as traction were the least generated benefits irrespective of wealth group categories, while milk and hides/wool have a similar maximum value.

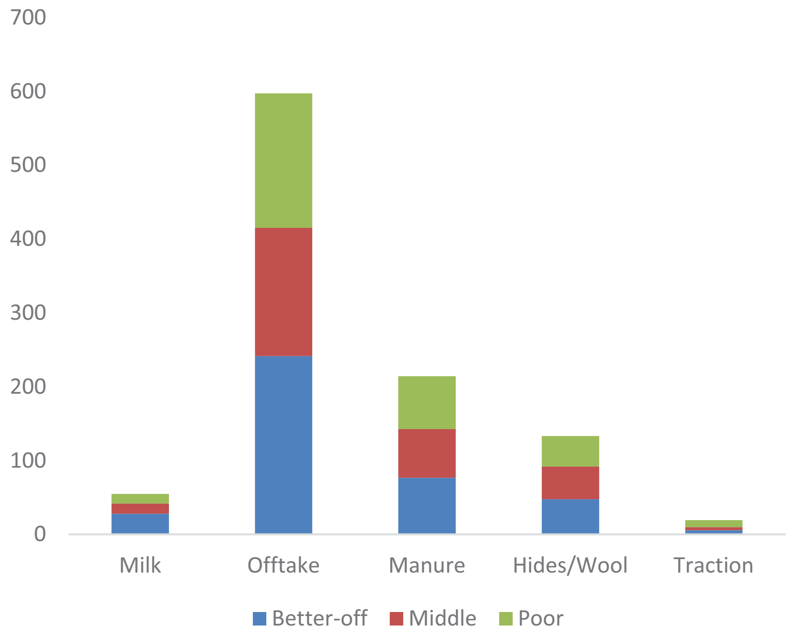

Figure 3.42 Proportion of estimated mean of livestock beneficial outputs contributed from livestock

3.3.4 Discussion

It is evident that the availability of household labour and livestock resources are the pillars of household productivity that stratify them into wealth group categories. These results are similar to those found by Kebebe et al. (2015) and Bekele et al. (2017), in which they showed a significant effect of resource legacy of households on the LWP. Wealthier households are better able to hire additional labour and buy supplementary feed than poor households. Furthermore, the high livestock numbers can possibly facilitate their ability to generate cash from livestock through sales. According to McDermott et al. 2010), labour is a prerequisite to carry a sound productive livestock management. The availability of labour has an important positive relationship as it improves production of livestock goods and services. According to Asfaw et al. (2011), family labour plays a significant role given that it's of a lower rate than wage labours. Although poor households can have family labour invested, it is evident that, still with the given livestock holdings, they cannot adequately sustain themselves.

TLU was higher in the wealthier households, followed by middle then poor households. This indicates that wealthier households stand a better chance to cultivate their croplands at the right season with adequate frequency of tillage for better land. Moreover, supported by Bekele et al. (2017), proper agronomic practices are mostly done when enough family labour is available. The overall derived beneficial outputs from livestock was almost similar across the wealth groups, however, wealthier households were higher than middle wealth and poor households. Higher overall outputs ultimately contribute to higher LWP. The differences obtained in beneficial outputs among wealth groups reflects the variation in total household livestock holdings among wealth group categories.

Mean LWP did not vary significantly among different wealth groups. Better-off households had higher LWP followed by middle group then poor households.

The numerator of the LWP equation summarises the net beneficial goods and services obtained from livestock, while the grouping of the wealth categories used standing livestock and dwelling type as an index of wealth. These results suggest that being considered as a wealthier household does not automatically mean higher LWP. A possible explanation to variations in LWP among wealth groups can be explained by the variations in livestock household holdings, access to labour and other household assets which was evident as wealthier households own more livestock than middle and poor households. Kebebe et al. (2015) stated that wealthier households stand an advantage for their high numbers of livestock to convert available feed to higher beneficial outputs such as milk, offtake, manure, traction and wool/hides.

Variations in LWP among different wealth group categories suggest the possibilities to improve LWP with the current level of knowledge given that farmers have better access to land, labour and oxen for traction. Water use in cultivated lands and areas around the homesteads was not included in the analysis because of the difficulties to successfully separate the two domains due to small gardens available in different households. This could possibly be the reason for differences in LWP among different wealth groups. For example, better-off households could have backyard gardens and be able to plant more feed for livestock than poor households. Kebebe et al. (2015) urge that, increased LWP is a result of increased feed efficiency utilised by the animals and increased water use efficiency through rainwater management.

Households use the advantage of keeping different livestock species to derive sustainable outputs and services using available resources. This study considered outputs such as milk, offtake, manure, hides/wool and traction to estimate the annual beneficial outputs derived from livestock in each household. Offtake was found to be the prime share of beneficial outputs derived from livestock followed by manure, but this varied among wealth groups (Table 3.7). Manure is very important in improving soil fertility replenishment and was the second-highest beneficial output reported in different wealth groups, followed by milk and traction. Wealthier households are possibly at an advantage of having an ability to replace traction animals due to their high numbers than poor households.

The differences in milk production among the different wealth groups is possibly that wealthier households are able to keep particular crossbred animals than poor farmers. Even though there is variation in milk production among the wealth groups, it contributes the least in the overall total annual outputs. However, milk production should not be undermined in this area, provided that good animal husbandry and management interventions are needed. The primary purpose of livestock keeping in a mixed farming is to maintain continuous livestock herd and compliment crop production. Bekele et al. (2017) suggest that an increased number of livestock in an individual household could lead to increased LWP in the short term. The finding of the study also reported wool/hides as one of the annual beneficial outputs derived from livestock in the study area. This also indicates the extent of willingness and different abilities of households to keep sheep.

3.4 NPP for IAPs - Patterns of wattle spread and projected NPP models

3.4.1 Introduction

Canopy LAI can be highly correlated with fPAR, NPP and biosphere–atmosphere exchange of heat, momentum and many important trace gases. The LAI and fPAR characterise canopy function and energy absorption capacity and are key parameters in most ecosystem productivity models and global models of climate, hydrology, biogeochemistry and ecology (Sellers et al. 1997). The production of stand biomass at a particular locality is determined not only by the absorbed solar radiation but also by the efficiency of conversion of this radiation energy into biomass (significantly determined by the stand structure) and the ‘quality’ of the locality, e.g. water and nutrition availability (Xu et al. 2006). Monteith and Moss (1977) reported a linear relationship between photosynthetically active radiation (PAR), which is absorbed by the stand, and above-ground dry matter production over relatively short time spans (i.e. days of the growing season). The linear character of this relationship is a great advantage and many empirical studies have supported this assumption (Madakadze et al. 1998). The rate of plant growth, and production of forage, depends on the size of the photosynthetic (leaf) area available for trapping sunlight and the efficiency with which this leaf area can photosynthesise. Thus determining LAI and fPAR can give an indication of NPP.

In this chapter LAI and fPAR field measurements and satellite-derived means for land covers found in catchments S50E and T35B are reported (Chapter 3.4.2) and this work has been published in Palmer et al. (2017). Historic patterns of wattle spread are then shown for the T12A catchment (Chapter 3.4.3) and was the subject matter of an Honours dissertation at Rhodes University by Chris Scorer (Scorer et al. 2018).

3.4.2 LAI and fPAR measurements

For this section, catchments with contrasting land tenure arrangements were selected (S50E and T35B) and field validation of satellite-derived fPAR and LAI for selected land cover classes was conducted. This information can then be used at catchment scale in hydrological and evapotranspiration models. The two catchments in the Great Kei and Tsitsa River primary catchments are representative of areas where IAPs are a threat to unimproved grasslands. These quaternary catchments contain a range of land cover types, including commercial forestry, commercial dryland cultivation (maize and soya bean), native forests, IAPs, wetlands, urban areas and unimproved grasslands. Both catchments have experienced extensive IAP invasion by three important aggressive taxa, namely black wattle (*Acacia mearnsii*), silver wattle (*Acacia dealbata*) and poplar (*Populus* spp.), with IAP clearing operations having been initiated by the WfW programme of the DEA.

The LAI of a subsample of nine sites was measured using an AccuPAR Ceptometer model LP-80 PAR/LAI (Decagon Devices, Pullman, WA, USA). LAI and fPAR was measured at selected examples of nine land cover classes and examples of areas invaded by IAPs during a field campaign in January 2014 as this is regarded as the peak of the growing season in this region. A weather station at nearby Maclear had received 350 mm of rainfall in the preceding 120 d. At each site, repeated (10) recordings of LAI and fPAR were recorded on cloudless days between 11:00 and 13:00. All readings for each land cover class encountered in the study area were used to calculate a mean fPAR and LAI per cover class, and to provide full descriptive statistics that can be used in net ecosystem exchange (NEE) and ET models.

A Landsat 8 image of the study area was acquired for 16 January 2014 (within 7 d of the field survey) and NDVI was calculated. Using the geolocation information for each land cover class, a mean NDVI for each cover class was extracted using a 20-pixel sampling window. These are the first reported measurements of fPAR and LAI values for samples from several land cover types, plantations and crops for sites in these catchments. The highest mean LAI value (x = 7.38) for the entire study area was recorded under a monospecific plantation of black wattle in the riparian zone, adjacent to a village on communal land (Table 3.8). The second-highest LAI occurred in an actively growing stand of black wattle upon a rocky slope on former commercial rangeland. The mature eucalyptus plantation had the lowest LAI and fPAR when compared with all other cover types at the peak of the growing season. Native grassland and immature pine plantation both had lower LAI and fPAR values than the other selected examples of land cover. There was a significant, positive correlation between the field-measured LAI and the NDVI from the Landsat 8 image of 16 January 2014 (F value = 38.57, $p < 0.001$). The proportion of land surface that each cover class occupies in the two quaternary catchments in this study shows that native forest and IAPs together currently occupy 12.3% (T35B) and 10.8% (S50E) of quaternary catchment area (Münch et al. 2017). The results indicate that there are extremely high LAI values associated with stands of mature black wattle, and suggest that these IAPs are significant users of water in these landscapes relative to all other land cover classes.

The strong positive relationship between the in-field measurements of LAI and the Landsat 8 NDVI indicates that it will be possible to apply the results of the in-field validation of LAI to the entire catchment. The fraction of PAR intercepted by all of the plant canopies was greater than 0.9 in all but three of the land cover classes (Table 3.8). This indicates that in-field measurements were recorded when active growth was at or close to maximum, thereby providing maximum possible values for LAI, fPAR and ET for each of these cover classes.

Table 3.8 Mean LAI and fPAR for selected land cover classes

Land cover class	Mean LAI	Mean fPAR
Native grassland	3.84	0.84
Mature pine plantation (>15 years)	5.21	0.94
Immature pine plantation (<3 years)	3.27	0.78
Mature eucalyptus plantation	2.09	0.66
Native wetland	4.25	0.92
Mature maize (commercial dryland)	4.61	0.89
Black wattle on shallow rocky soils on slope	6.05	0.96
Black wattle in riparian zone	7.38	0.97
Mixed black wattle and gum in riparian zone	5.90	0.93

3.4.3 IAPs spread

3.4.3.1 Introduction

IAPs are a threat to ecosystem integrity in many parts of the world as they are naturalised plants whose high reproductive potential and the ability to spread over distances makes them successful and often threatening to the local biodiversity, ecosystem functioning and the services derived from these ecosystems (Richardson et al. 2000; van Wilgen et al. 2012; Vaz et al. 2017). IAPs are estimated to use about 17% of the total water use in the Eastern Cape (Le Maitre et al. 2000). Effective ways of controlling the spread of IAPs is through three potential strategies of prevention of an outbreak, early detection, and eradication (McConnachie et al. 2012). However, when dealing with large scale, well-established infestations, costly clearing strategies have been implemented to remove IAPs (McConnachie et al. 2012), such as the WfW programme in South Africa. WfW links socio-economic development with ecosystem health and it was established as a poverty relief programme in 1995 and the programme involves poor and disadvantaged people to clear areas of alien vegetation from water courses and river catchments (Macdonald 2004; Oelofse et al. 2016). An evaluation after 15 years of operation of WfW found that the necessary control operations were present in only a small section of invaded areas and that the invasions were increasing (van Wilgen et al. 2012).

Quaternary T12A in the Eastern Cape is located in the upper reaches of the Mgwali River with Drakensburg Foothill Moist Grassland and Tsomo Grassland as the dominant land cover (Mucina and Rutherford 2006). This catchment has been subjected to widespread alteration by agrarian intensification and human development (Münch et al. 2017). The catchment has been designated as high priority for clearing by the Generic Synthesis Prioritisation Model (Le Maitre et al. 2012; Wannenburgh 2015), has substantial stands of *Acacia mearnsii* and *A. dealbata*, and WfW have been clearing for the past 15 years (Wannenburgh 2015). In the northern parts of the catchment, the trees appear to have been extensively used as windbreaks by farmers to provide shelter for livestock, and as woodlots for fuelwood, and the main form of land disturbance is crop farming and plantations. Notably, abandoned farmlands that are no longer in operation, are vulnerable to infestation by the pioneering *Acacia mearnsii* species which quickly establish on disturbed and cleared lands (de Neergaard et al. 2005).

3.4.3.2 Method

Two scenarios of disturbance were compared for quantifying the magnitude and direction of change in *A. mearnsii* infestation using land cover change detection analysis: disturbed grassland (with abandoned farmlands) and undisturbed grassland (also referred to as 'unimproved grassland' in the South African National Land Cover (NLC) classification NLC 2000; van den Berg et al. 2008). Aerial imagery from four time periods, separated by at least a decade (1958/9, 1976, 1995 and 2009; Director General, Surveys and Mapping, Department of Rural Development and Land Affairs), were georeferenced using ArcGIS 10.3.1 and three replicate sites with initial stands of *A. mearnsii* for each scenario type, i.e. disturbed and undisturbed grasslands, were chosen. A grid of ~400 cells (23 x 17 cells of ~50 m x 50 m) was placed over each study site, and each cell was classified into one of six land cover class types based on the dominant class that could be visually distinguished: a) unimproved grassland (areas with little to no human disturbance), b) riparian (areas situated on the banks of a river), c) disturbed grassland (areas that appear to have been cultivated in the past), d) *A. mearnsii* trees, e) cleared *A. mearnsii* areas, and f) natural forest (areas covered by naturally occurring tree/forest species). The earliest set of imagery (1958/9) was used to assign each cell with an initial class type which in later time period imagery either remained the same (implying no change) or shifted into another class type (i.e. change occurred). Counts of each land cover class at each replicate site were quantified for determining the trends in land cover change over the three time periods.

The second component of the study estimated the standing biomass and modelled the growth of *A. mearnsii* using calculations of DBH (Diameter at Breast Height) and stem density (stems ha^{-1}) with the point-centred quarter (PCQ; Cottam and Curtis 1956) method along the stand-age gradient. The current above-ground biomass was estimated using a tree allometry equation linking DBH to total standing biomass (Paul et al. 2013) for *A. mearnsii*. Based on the chrono-sequence of the aerial photographs, estimates of the approximate age of each stand were made in order to provide a biomass by age sequence for predicting annual growth (ton ha^{-1} yr^{-1}). These annual growth estimates were validated against the MODIS NPP (Mu et al. 2011) product from 2000 to 2013 that was extracted for some of the sample sites.

3.4.3.3 Results

A clear distinction was visible between the rate of spread of *A. mearnsii* species in areas that were classified as undisturbed versus disturbed grassland areas with abandoned cultivation. A slight increase in the *A. mearnsii* cell counts and a corresponding decrease in the unimproved grassland cells was noted at the undisturbed grassland sites in contrast to a larger decline in unimproved grassland cells and an increase of between 2–10 times for *A. mearnsii* cells at the replicate disturbed sites.

These observations are supported by the data on the changes between land cover class changes for the three time periods; while some grassland cells changed to *A. mearnsii* at both scenario sites, land cover change at disturbed sites was dominated by abandoned cultivation cells transitioning to new invasions of *A. mearnsii* land cover at a greater rate instead of reverting to the original grassland land cover.

These results indicate the vulnerability of disturbed grasslands with abandoned cultivation areas to infestation by the rapid establishment of *A. mearnsii* trees. Other land cover class changes were small/negligible in the number of cells involved for both scenarios.

The total above-ground standing biomass varied from 170 ton ha^{-1} to over 550 ton ha^{-1} with a mean of 295 ton ha^{-1} (n=32). The growth model showed an increase of 10 ton of carbon ha^{-1} yr^{-1} with a levelling off at around 400 ton ha^{-1}. MODIS NPP data validated the incremental annual rate of 10 ton ha^{-1} yr^{-1}, which is the total carbon including root biomass that could account for 0.5 to 0.67% of total biomass (DEA 2015).

3.5 Conclusions

Livestock production is an effective practical way out of poverty in rural livelihoods. There are opportunities that exist to improve LWP at scales of household levels such as labour and providing additional livestock feed. The positive relationship between livestock holdings with LWP and labour with LWP among wealth groups suggests that strategies to improve water use need to focus on feed and labour.

Considering that the study area is a mixed crop-livestock system, complementary interventions can be suggested to increase WP in different households. Improved production could be through promoting crossbreeding (Scholtz and Theunissen 2010), improved health care, improved supplementary feeds, improved use of livestock services and improved labour provision. This will in turn boost the capacity of all household group categories to achieve improved LWP. The findings of this research can help in making a decision on where to invest the resources to achieve an increased LWP in a communal production system.

The changing of natural regimes by conservation, commercial forestry, intensive agriculture, and urban development has an influence on the way trees grow on a landscape (Geldenhuys 2004). Invader plants are typically pioneers that are the first to establish in areas which have been disturbed. It has been shown in this chapter that LAI and fPAR of IAPs is higher than that of other land covers and also that already disturbed areas are more likely to become invaded by IAPs.

CHAPTER 4 COMPARISON OF ET, LWP AND NPP IN THREE CATCHMENTS AND APPLICATION OF SELECTED MODELS FOR PREDICTING ET, LWP AND NPP

By

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4.1 Introduction

This chapter addresses Aims 2 and 3 of the project, and reports on the dynamics in ET and vegetation biomass in three quaternary catchments (T12A, S50E and T35B). Both *in situ* measurements and remotely-sensed data were applied in characterising ET and biomass. To begin with, comparison of the PML and PMP models of ET is presented. The models were validated with ET derived from a LAS. Next a new parsimonious model is presented as an improvement of the PMP model over the short canopies. The new model was validated with ET derived from scintillometer in the grassland and an EC in the Albany Thicket (AT). The chapter also goes further to illustrate the impact of land cover change on ET and NPP using essentially, remotely-sensed data. Further, the concept of LWP is explored and variations in livestock productivity in different wealth categories are presented. An evaluation of the impact of *A. mearnsii* on soil variables is presented and the impact of clearing of *A. mearnsii* on grass production is illustrated. Optimum ways of rangeland management in a context of *A. mearnsii* invasion are explored. Finally, future land cover scenarios (2030) are predicted.

4.2 Measurement and modelling of ET

In developing countries where there is paucity of data, developing and testing parsimonious ET models is critical for IWRM. However, ET is one of the least understood processes of the hydrological cycle, owing to the difficulties inherent in measuring it (Amatya et al. 2016). A number of ET models have evolved, ranging from radiation, combination, energy balance and temperature-based algorithms (Mu et al. 2011; Liou and Kar 2014; Zhang et al. 2016). The PM equation is one of the most theoretically robust ET models, which is essentially driven by routine meteorological data from weather stations (Fisher et al. 2008; Leuning et al. 2008). The PM equation evolved as a single layer potential ET model (Penman 1948; Monteith 1965), but recent efforts have enhanced its skill to also account for soil evaporation (E_s). Due to the robustness of the PM equation and data availability, this study adopted two recent models based on the original PM equation to compare their performance over a grassland area in South Africa. These models include the PML (Leuning et al. 2008; Morillas et al. 2013) and a method described by Palmer et al. (2014), herein called PMP. The main difference in the approaches is that, the PMP model uses LAI as a scalar while the PML uses G_c and the f to constrain ET.

4.2.1 Comparison of the performance of the PML and PMP models over the grassland

The study compared the performance of the PML and the PMP models over mesic grasslands in the northern Eastern Cape with LAS data being used for validating the two models. The first experimental site was at the Truro farm and the second site was Somerton farm. Details of the logistics for applying the two models, experimental set up and data analysis can be found in Gwate et al. (2018a).

Results

The terrain at both experimental sites was not gentle with effective height at 3.83 m at Truro farm while at Somerton farm, it was 3.05 m. Of the available data, 7% and 35% of hourly fluxes were filtered out due to failure to pass quality control flags in Truro and Somerton sites, respectively. LAS saturation would start at C_n^2>1.85498 x 10^{-9} and 9.3334 x 10^{-10} at the Truro and Somerton sites, respectively. Fortunately, LAS saturation did not occur during the study at either of the sites.

Model parameter estimation

Owing to logistical challenges, data collection at Truro farm was quite short (43 days) and as such the PML model was calibrated at Somerton farm and validated at both sites. Optimised values for the PML model are presented in Gwate et al. (2018a). The PMP model does not require any calibration and hence it was validated at both sites.

Validation of the two models at the Somerton and Truro farms

All the PML approaches (f_{drying}, f_{zhang} and f_{SWC}) yielded RMSE that was within 15% of the daily observed ET at Somerton farm while the PMP model largely underestimated ET. At the Truro farm, the PML approaches still performed better (RMSE <20% of average measured ET) than the PMP model. For details, readers are referred to Gwate et al. (2018a).

Discussion

Given that a number of data quality control checks were undertaken (Gwate et al. 2018a) the results of calibrated parameters and modelled ET are credible. The g_{sx} values were slightly lower than the optimised values obtained by Leuning et al. (2008), who obtained a value of

0.0048 ms^{-1} over a grassland, but the observed values were within the range reported by Kelliher et al. (1995). Stomatal conductance was also measured in the field at Somerton farm and the highest value obtained was 0.0025 $m \cdot s^{-1}$ (Gwate et al. 2018a). The relatively low stomatal conductance was not surprising given that vegetation in the two sites (*Themeda trianda* and *Eragrostis curvula*) evolved to survive in dry environments. The low α (0.1) could be reflective of relatively high soil water content (SWC).

Results suggest that the f_{drying} approach outperformed other PML approaches and the PMP model in reproducing ET dynamics. The slight over-prediction by the f_{drying} approach was due to the higher *f* values considered by the model, probably due to relatively high precipitation during the validation period at the Somerton site. There were only a few rainy days during validation, at Truro, resulting in lower *f* values and hence the slight underestimations by the model at this site. The f_{zhang} approach overestimated ET and this was consistent with results from elsewhere (Morillas et al. 2013; Zhang et al. 2016) since when applied on a daily interval, the f_{zhang} approach tended to over-predict ET, especially after rainfall events. Most of the RMSE was unsystematic for the PML model approaches and this is a hallmark of robust models (Willmott 1981; Leuning et al. 2008). The RMSE and mean absolute error (MAE) for the different PML approaches were significantly lower, relative to mean daily measured ET, and this suggests that the model was quite robust. The sensitivity of the PML model to aerodynamic components and the need to accurately define the wind speed at canopy was demonstrated in Chapter 3 of this report. On the other hand, the PMP model performed poorly, indicating that constraining reference crop evapotranspiration (ET0) to actual ET using the LAI as a scalar was inadequate in grasslands with LAI < 2. In such areas soil evaporation (E_s) could be > 80% (Gwate 2018).

4.2.2 Improvements in ET estimates using a parsimonious approach

Parsimonious ET models are attractive particularly for data scarce regions. However, the foregoing section showed the inadequacy of the parsimonious PMP model in grasslands that had LAI <2. In such areas, E_s contributes greatly to the total flux (Leuning et al. 2008; Mu et al. 2011; Morillas et al. 2013). It should be noted that, models that use vegetation indices such as normalised difference vegetation index (NDVI), LAI or crop coefficients do not estimate E_s. As such the PMP model was found inadequate in grasslands with LAI <1 (Gwate et al. 2018a). Nevertheless, Palmer et al. (2014) reported good performance by the PMP model over a savanna woodland in Skhukhuza. Therefore, there is need to improve the PMP model to better simulate ET in grasslands as well. This section reports on the improvements in the PMP model so that it captures E_s dynamics.

Methods

The study used data from the LAS (Gwate et al. 2018a) and data from an EC system at eZulu Game Reserve (Gwate et al. 2016a). To improve ET estimates a new model was proposed (Gwate et al., 2018d in press):

$$ET = \frac{LAI}{LAI_{max}} \text{x}\, ET_0 + f\frac{\varepsilon A_s}{\varepsilon+1}, \quad \text{Equation 4.1}$$

where A_s is energy available to the soil, and the logistics of its derivation can be found in Allen (1998) and Morillas et al. (2013). LAI_{max} is maximum LAI, ε is slope (Δ) of the curve relating saturation water vapour pressure to temperature divided by the psychrometric constant (γ), f is a factor modulating PET from the soil and ranges between 0 – 1.

The second part of equation 4.1 is used to calculate the E_s component. The model uses meteorological data widely available from weather stations and LAI from remote sensing. In addition, the model does not need any fine tuning with observed data as is the case with the PML model. The model was validated over the grassland at Somerton farm (N = 104 days), Truro farm (N = 29 days) and eZulu Game Reserve (EGR (N = 401 days)). ET derived using a LAS (Gwate et al. 2018a) and data from an EC system at EGR (Gwate et al.,2016a) were used to validate the new model. For details on experimental set up and data analysis readers are referred to Gwate et al. (2018) and Gwate et al. (2018a).

Results

The environmental conditions varied greatly at each experimental site. Although the EGR site had observations cutting across the growing (August-April) and non-growing season (May-July), the mean temperatures were similar across the sites. Relative humidity was highest at the Somerton site and lowest at the Truro site. Highest average wind speed was recorded at the Truro site. The Somerton site had the highest average net radiation (R_n) while the EGR site had the lowest mean R_n over the observation period. Average daily ET at Somerton was higher than that at Truro and EGR sites by 31 and 76% respectively. Mean ET0 was lower at EGR compared to the two grassland sites during the observation period. The average volumetric SWC pattern was in sync with the rainfall and the lowest SWC was observed at the EGR site. The SWC at the Somerton farm was 36 and 59% higher than at the Truro and EGR sites respectively. The LAI was < 2 across the sites but differed significantly as the Kruskal-Wallis test revealed ($p < 0.05$) with the lowest being observed at the EGR site. For details on environmental conditions, readers are referred to Gwate et al. (2018d, in press).

The improved PMP algorithm resulted in a RMSE of 0.58 mm day^{-1} at Somerton and 0.39 mm day^{-1} at Truro in a context where the observed daily mean ET was 3.24 and 2.23 mm respectively. At the EGR the RMSE was 0.50 mm day^{-1} and this was largely unsystematic in a context of a daily mean of 0.76 mm. The root mean square error observations standard deviation ratio (RSR) was similar (0.08 – 0.13) across sites. The model tended to slightly overestimate and underestimate observed ET at the Truro and Somerton sites, respectively, as shown by the percent bias (PBIAS). When data from the two grassland sites were combined the RMSE was within 18% of the observed mean daily ET against the modelled of 3 ± 1.55 mm. Modelled soil evaporation accounted for 69, 65 and 84% of the total modelled ET at Truro, Somerton and EGR respectively. Details of these results can be found in Gwate et al. (2018d, in press).

At the EGR the growing (August-April) and non-growing season (May-July) RMSE were 0.51 and 0.3 mm day^{-1} respectively and the PBIAS was negative for both seasons. In the non-growing season, the average EC ET was 0.43 ± 0.49 while in the growing season it was 0.85 ± 0.66. Using linear and non-linear regression, the relationship between VIs and ET was weak ($R^2 \leq 0.3$). The study found a relatively moderate correlation between ET and VI at the study sites. However, NDVI had a better correlation with ET ($p < 0.05$) while the relationship between Enhanced Vegetation Index (EVI) and ET was insignificant at EGR ($p > 0.05$). NDVI was better correlated with ET than EVI across the sites. Using multiple linear regressions, the 8-day average LAI and 8-day accumulated ET0 were regressed against the observed 8-day accumulated ET. At the EGR, strong relations were observed ($R^2 = 0.35$, $F = 11.92$, $p < 0.001$, N = 51, 8 day periods). The equation is expressed as:

$$\mathrm{ET} = 16 \times \mathrm{LAI} + 0.004 \times \mathrm{ET0} - 0.17 \qquad \text{Equation 4.2}$$

Using the combined data from the grassland sites, significant relationships were also found ($R^2 = 0.65$, $F = 16.73$, $p < 0.001$, N = 20, 8-day periods) and the equation was:

$$\mathrm{ET} = 14.19 \times \mathrm{LAI} + 0.58 \times \mathrm{ET0} - 14.1 \qquad \text{Equation 4.3}$$

Discussion

The validation took place under varied environmental conditions and the improved model was largely able to capture the dynamics of measured ET (Table 4.3) despite, uncertainties connected to input data such as MOD15A2 LAI and MCD43B surface albedo. The tendency to overestimate ET at the EGR site was due to overestimated E_s and possibly the underestimated latent heat flux (LE) as shown by poor energy balance closure reported in Gwate (2018). However, in the EGR, the dominant shrub, *P. afra,* could have been exercising greater stomatal control, resulting in high water use efficiency (Mills and Cowling 2006). Admittedly, grasslands may also exercise great stomatal control over ET (Snyman et al. 2013; Favaretto et al. 2015) but *P. afra* has a higher water use efficiency, and hence its widespread environmental plantings in South Africa under the auspices of the Clean Development Mechanism (Mills and Cowling 2006). Therefore, the available leaf area may not necessarily be reflective of ET taking place as changes in stomatal behaviour greatly influence the water vapour flux. Glenn et al. (2010) observed that ET models based on VIs are not able to estimate E_s and stomatal conductance which affect total ET. Hence, the overestimation bias could be indicative of the model's limitations in reproducing the stomatal behaviour. The overestimation by the model can be reduced by a careful choice of the number of days (N) to be used in the determination of the *f* value. Sensitivity analysis of such approaches has shown that increasing N reduces overestimation and the optimum N lies between 16 and 20 days (Morillas et al. 2013). Despite the over estimation, on an annual basis, the model reproduced the measured ET with a relatively low RMSE from the EGR site despite the complex nature of the environment. In addition, across sites, the RMSE was largely unsystematic and this suggests that the proposed algorithm is robust (Willmott 1981; Leuning et al. 2008). Using similar approaches of modelling E_s, good agreement between tower observed ET and modelled ET across many catchments have been recorded (Morillas et al.,2013; Zhang et al. 2010, 2016). The good performance of the proposed algorithm is very important particularly for data scarce areas. The model allows for ET to be calculated using routine meteorological data, surface albedo and the LAI without the need for fine tuning with observed data. These data are readily available in sparsely distributed weather stations and from remote sensing.

Attempts to predict ET from vegetation indices (VIs) was not successful probably due to the low VIs and LAI (0.1 – 1.8). It is well-established that in areas with LAI < 2.5, E_s is crucial and could account for ~ 80% of total evaporation (Leuning et al. 2008; Morillas et al. 2013). This could have been aggravated by the possible role of stomatal control. This suggests that much of the water is consumed through the so-called 'unproductive' or 'white' evaporation and hence there is scope for improving WP across the study sites. However, robust relations were developed through multivariate regression of ET0 and LAI against measured ET. Subsequently equation 4.2 was validated by Gwate et al. (2018b) and the RMSE was 0.28 mm day^{-1} in a context where the average daily ET was 0.87 mm. This indicate that the predictive equation was robust for the AT biome.

Although the algorithm performed well, there are uncertainties stemming from the calculation of *f* values and general input data. It should be noted that the movement of water between the upper soil layers and groundwater is not well understood (Wilcox 2010). Wu et al. (2015) found that even shallow rooted plants like grasslands can use ground water by exploiting the capillary rise fluxes. Other uncertainties are connected to the MODIS LAI used in the model (McColl et al. 2011; Serbin et al. 2013). The process of selecting the highest LAI for a particular pixel is also vital and could result in model uncertainties. In situations where land cover was not persistent, this could be problematic and great care should be taken to ensure that maximum LAI relevant to the particular land cover type is retrieved.

4.2.3 Impact of land cover change on evapotranspiration in mesic grasslands

Land cover change is a pervasive force and it influences the partitioning of precipitation (*P*) into other components of the hydrological cycle such as ET and runoff. The influence of land cover change on hydrological fluxes has been the subject of long-term interrogation across the globe (Zhou et al. 2015). Therefore, understanding the temporal and spatial dynamics actual ET (AET) in a context of global environmental changes linked to climate and land cover changes is crucial. In South Africa, IAPs, together with changes in the extent of dryland cultivation and human settlements are the main drivers of land cover change. These changes have a serious consequence on surface albedo which in turn affects energy balance. It is well-established that increasing albedo has a cooling effect which in turn influences atmospheric turbulence and biogeochemical cycles (Houspanossian et al. 2017). Grasslands are vital in supporting world agriculture and providing other ecosystem services. Therefore, it becomes important to determine the response of grassland ecohydrological processes such as AET to land cover changes. Globally, research on the link between hydrological fluxes and land cover change has yielded different results (Zhou et al. 2015). However, it is well-established that conversion from shallow rooted vegetation to long rooted ones such as forest results in an increase in ET and undermine catchment yield (Zhang et al. 2001). AET is the biggest flux of the hydrological cycle after precipitation and it is critical in determining water availability at a place (Mu et al. 2011). Global change studies project future water scarcity in many parts of the world. Therefore, it becomes imperative to understand AET for each land cover type in a given system as change of land cover in water-limited systems may lead to conflicts around water allocation and licensing (Vettorazzi and Valente 2016). In South Africa, forestry, livestock grazing, cultivation, as well as rural and urban settlement arguably represents such a conflicting space. Therefore, quantifying AET in each land cover class can provide valuable information to water regulators in their attempts to resolve these conflicts. Hence, it becomes important to determine the AET response to land cover change in grasslands of South Africa.

However, linking change in hydrological fluxes to land cover change is a daunting task. The Budyko theoretical framework (Budyko 1974) has been used extensively to estimate long-term actual evaporation as a function of the aridity index at mean annual time scale. This framework relates the evaporative index (AET/P) to the dryness index (PET/P), where P denotes mean annual precipitation (rainfall) and PET is potential evapotranspiration. The framework assumes that the mean annual evapotranspiration over a large area is controlled by water availability and VPD or its proxy, net radiation. Water availability is approximately equivalent to precipitation and provides water for ET while VPD is indicative of atmospheric demand for water. Notwithstanding other biophysical controls such as stomatal conductance and wind speed, high AET rates are expected in areas of high VPD. Based on the Budyko framework, under very dry conditions, AET will approach precipitation, and under very wet conditions, evapotranspiration will asymptotically approach the atmospheric demand or its proxy, net radiation, at mean annual time scale (Wang et al. 2016).

The original Budyko framework did not consider vegetation cover and other catchment characteristics since the long-term AET of a system was seen as a function of *P* and PET. However, recently, variants of the original Budyko theoretical framework have been used to estimate catchment AET by incorporating catchment characteristics such as land cover and soil moisture (Zhang et al. 2004; Chen et al. 2015). These approaches allow some hydrological processes to be calculated on an annual basis in both small and large catchments (Zhou et al. 2015; Chen et al. 2015). Essentially, these frameworks mainly use a single parameter to represent catchment characteristics related to land cover (Chen et al. 2015). This study adopted the formulation first described by B.P. Fu (in Chinese) as reported in literature (Zhang et al. 2004; Chen et al. 2015) to parameterize a catchment parameter (w) that incorporates catchment properties connected to land cover on an annual basis. The model is expressed as:

$$AET/P = 1 + PET/P - [1 + (PET/P)^{w}]^{1/w} \quad \text{Equation 4.4}$$

Where w is a model parameter varying from 1 to infinity and indicates the integrated catchment characteristics such as vegetation cover, soil properties and slope.

At the same time some factors, such as topographic and geologic properties, remain relatively the same over centuries while vegetation is dynamic even over short periods of less than a decade (Roderick and Farquhar 2011). Results from studies adopting equation 4.4 have helped to evaluate the impacts of land cover change on catchment hydrological fluxes (Zhang et al. 2001, 2004; Chen et al. 2015; Zhou et al. 2015).

Land cover change is a global phenomenon mainly driven by agriculture and settlement expansion (Lambin et al. 2003). Land cover maps provide a static view of the cover situation at a particular time and give an impression of abrupt shift from one cover type to another. Hence, in an attempt to understand the response of AET to land cover change it is important to detect the onset of change in AET in response to the generally slow process of land cover change. However, this is often a difficult task, but a very important one to correctly attribute fluxes to land cover change. Therefore, robust statistical methods of searching for breaks in longitudinal data become critical. At the same time, the evaporative index (AET/P) can also be a useful indicator to discern the influence of land cover dynamics on AET since it is essentially a function of the dominant land cover connected to the dominant land cover e it is part. To understand the response of catchment scale AET to land cover changes, quaternary catchment S50E (447.6 km^2) was selected in South Africa. Details of catchment characteristics can be found in (Gwate et al. 2018b).

Methods

Land cover maps for the year 2000 (Fairbanks et al. 2000) and 2014 (Okoye 2016) were used to extract ET values from the MOD16A3 ET (Mu et al. 2011). Since land cover change is a slow process, the study applied the method of cumulative residuals (Allen et al. 1998) to detect breaks in the AET pattern between 2000 and 2014. The point of break was in the year 2004 and hence the 2000 land cover map was used to extract ET values up to the year 2003 while from 2004 to 2014, the Okoye (2016) was used (Gwate et al. 2018a). To determine the impact of land cover change on ET, the evaporative index (AET/P) for each year was prepared. In addition, the *w* was estimated using optimisation by fitting equation 4.4 to AET from the MOD16A3 product in the R-3.1.3 software environment by exploiting the *rgenoud* package. Rainfall data was obtained from Tropical Applications of Meteorology Using Satellite Data and Ground-Based Observations (TAMSAT) dataset (Maidment et al. 2014; Tarnavsky et al. 2014). Rainfall and AET data were subjected to trend and step change tests to determine their trajectories (Gwate et al. 2018c). To determine the suitability of the rainfall and ET data sets used in this study, the two were validated. ET data was validated using scintillometer derived ET (Gwate et al. 2018c) and results showed that measured ET was significantly higher than the MOD16A2 ET during the validation period while the TAMSAT data was validated with weather station data (Gwate 2018) and the two were similar.

The shortened water balance equation was applied on quaternary catchment S50E using TAMSAT rainfall and MOD16 ET data. Gwate showed that the water balance derived using data from this study was consistent with other studies (Bailey and Pitman 2015). This indicates that the TAMSAT and MOD16 ET data were reflective of actual processes at catchment S50E and this suggests that the data derived in this study is valid.

Results

The PET was consistently higher than AET throughout the period and dry years coincided with relatively higher AET comparative to rainfall while years of higher rainfall coincided with reduced AET. With respect to total catchment rainfall and AET, no significant step changes or trends were detected during the study period (2000 to 2014) although the Sen's slope estimator showed that mean annual rainfall has been falling at a rate of 7 mm yr^{-1} within -9 and -4.84 confidence interval. Mean annual AET was falling at a rate of 2.4 mm yr^{-1} within -3.13

and -1.51 confidence interval. To get an insight into the regional rainfall pattern, long-term observed data from Mount Ayliff (1923 to 1985) which is 100 km awayin the same rainfall zone (Schulze 1997) also indicate an annual decrease in rainfall of 1.8 mm yr^{-1} within -2.53 and -1.03 confidence interval. When observed rainfall data from Mount Ayliff was combined with the TAMSAT dataset to cover the whole period upto 2014, an annual rate of 0.61 mm (confidence interval -1.1 and -0.21) decline in rainfall was still observed albeit statistically insignificant. During the study period (2000 to 2014), Pettit's test detected abrupt change ($p < 0.05$) in AET for grassland and the built-up land cover classes. The Mann-Kendall test detected a marginally significant trend ($p < 0.1$) in forest cover class AET during the study period. No statistically significant trends were detected with respect to other land cover types. The Kendall's tau statistic for forest (0.33) cover indicate increasing trend in AET while cultivation (-0.03) and plantation (-3.54) indicated a declining trajectory in the AET during the study period.

The Sen's slope showed that grasslands had highest AET annual rate of increase followed by built-up and forest cover types during the study period (2000 to 2014). On the other hand, cultivation and plantation cover classes experienced annual decrease in AET. Over the 15 year period the average catchment parameter (w) was 1.88 and ranged from 1.43 to 2.14. The Mann-Kendall test revealed a statistically significant decreasing trend in w in the quaternary catchment ($p < 0.05$).

To link land cover change to changes in the evaporative index, the study selected the important land cover types in the catchment that include grassland, plantation, forest, cultivation and built-up areas for further evaluation. During the period under review, increases in forest (98%), cultivation (264%) and built-up (64%) land cover types were noted. On the other hand, declines were observed in grassland (25%) and plantation (54%). Land cover change was accompanied by changes in the AET/P ratio. The decline in the plantation cover type coincided with 18% decline in the evaporative index. However, the reduction in grassland cover was accompanied by an increase in the AET/P ratio. The evaporative index for other selected land cover types increased remarkably with AET/P ratios being higher (4.9–31%) in 2014 compared to the year 2000. To determine the impact of woody encroachment on the evaporative index, grassland, plantation and forest cover were selected. The evaporative index for the grassland cover was lower (0.6–1.2) compared to that of plantation (0.94–1.73) and forest (0.82–1.5) land cover types. During years of lower rainfall (< 450 mm) the evaporation index was relatively high for both grassland and woody cover types while during the years of high rainfall (> 550 mm) the evaporative index was relatively lower.

Discussion

The results illustrate uncertainties inherent in satellite-derived AET as described in literature (Savage et al. 2004; Gwate et al. 2018a; Mu et al. 2011; Ramoelo et al. 2014; Zhao et al. 2005). The declining AET pattern is consistent with other studies (Eamus and Palmer 2007; Hoffman et al. 2011; McVicar et al. 2012). The reported densification by *A. mearnsii* in the study area (Gwate et al. 2016c) could have resulted in a trend observed in the AET of the forest cover class (Gwate et al. 2018c). For the plantation cover, the decrease in land cover was accompanied by a decline in evaporative index due to clear-felling of plantation and replacing it with a new crop.

The increase in cultivated land also had corresponding effect on AET since such crops tend to have a higher LAI during the growing season. Rainfall in the study area mainly occurs during the growing season and hence most of the rainfall received over cultivated land was consumed through AET. The step change in AET observed in the built-up area is indicative of rapid settlement in the catchment. Results also suggest that land cover change may not fully explain dynamics in grassland AET but a combination of factors such as land management linked to fire exclusion and also global forces related to warming (Gwate et al. 2018c). These factors could have possibly led to a step change in grassland AET.

Results revealed that the *w* was decreasing on an annual basis and this was indicative of dynamics in catchment characteristics related to the land cover change signal. It is well-established that the equations in the form of equation 4.4 are less sensitive to climate factors since these are captured in the index of dryness within the equation (Zhang et al. 2004; Chen et al. 2015), but are more sensitive to short term changes such as land cover. In addition, vegetation cover serves as a very good integrated indicator of other catchment characteristics such as soil properties while some catchment properties such as geologic and topographic ones do not change for centuries (Roderick and Farquhar 2011; Li et al. 2013) and hence, *w* is essentially indicative of vegetation characteristics. The breakpoint in this small AET dataset between 2003 and 2004 also suggests that the influence of factors other than climate were also crucial and in the short term these are captured within the vegetation characteristics (Roderick and Farquhar 2011; Li et al. 2013).

The *w* also indicates the ability of a watershed to retain water for evapotranspiration; larger *w* values mean larger and longer water retention capacities (Zhou et al. 2015). The *w* was declining and this suggests that the ability of the catchment to store water was falling (Zhou et al. 2015). This could be due to the observed densification of woody plants (Gwate et al. 2016c) that have higher AET compared to the native grasslands in the catchment resulting in the depletion of soil moisture. The present study found an average *w* of 1.88 and this was within the observed $1 < w < 2$ threshold used to diagnose the sensitivity of a catchment to land cover change (Zhou et al. 2015). It is well-established that hydrological responses to land cover changes are more sensitive when watersheds have lower water retention capacity as indicated by the critical thresholds of $1 < w < 2$ (Zhou et al. 2015). On the other hand, in areas with $w > 2$, the hydrological response of catchments was more coupled to P/PET. Looking into the future, management interventions are required in this catchment in order to reduce the deleterious effects of land cover change since the *w* suggests that the catchment was sensitive to such dynamics.

Although on a catchment basis, the Sen's slope of rainfall and AET showed a decreasing trajectory, some land types recorded mean annual increase in AET. Theoretically, one would expect corresponding decrease in AET across the land cover types since precipitation is the main driver of AET. Admittedly, extra water to drive AET could have come from runoff or ground water being accessed by long roots as well as capillary action for specific land cover types. This indicates the potential influence of non-steady state characteristics at the catchment. This suggests that land cover change could have serious hydrologic effects and also affect grassland ecosystem services. Although increase in cultivated land was accompanied by a corresponding increase in the evaporative index, the decreasing AET trajectory could be linked to stomata closure to optimise water use under conditions of moisture deficit as recognised by Hernández et al. (2015) with respect to maize (*Zea mays*) in water-limited environments.

At times AET exceeded rainfall and this may have been caused by additional moisture from runoff along the rivers since a perennial river drains the quaternary catchment as well as rooting depth. The observed evaporative index for different vegetation were consistent with the basic premise of the Budyko framework that in water-limited ecosystems, AET approaches and may exceed precipitation if there is additional water supply. PET was consistently higher than AET and rainfall throughout the study period, suggesting that there was high atmospheric demand and more energy was available to drive AET. The results also show that during the years of lower annual mean rainfall, the evaporative index for either grassland or woody vegetation cover tended to be higher. This may be linked to the high VPD associated with dry conditions resulting in a higher evaporative flux. Results were consistent with the theoretical framework of Zhang et al. (2004) that systems dominated by woody vegetation tend to have higher AET compared to those dominated by grasses.

4.3 Exploring LWP at quaternary catchment T12A

Improving WP in agriculture is vital in the context of water scarcity. This section presents a baseline on LWP at Cala communal lands (catchment T12A) in the Eastern Cape. LWP was calculated using equation 3.11 presented in section 3.3.2.

4.3.1 Results

The results of the analysis showing the comparisons of mean livestock beneficial goods and services quantified separately on annual basis and converted into monetary values among the different wealth groups are presented in Table 4.6. The results revealed a variation in terms of individual beneficial goods and services derived from livestock by different wealth groups. However, a significant variation was reported between better-off and poor households except for wool, which was similar across the three groups. Milk, offtake and traction was higher in better-off households, while middle and poor were similar. Manure production was different among the wealth groups with better-off households obtaining high manure followed by middle then poor households. Overall, significant differences in beneficial goods and services corresponded with wealth status being higher in better-off and lower on poor households. Table 4.1 illustrates mean LWP obtained in the study site. There were no variations in mean LWP obtained by different wealth groups. Better-off households obtained high LWP (0.32) followed by the middle (0.31) and poor households (0.30).

Table 4.1 Livestock outputs and mean LWP.

Livestock beneficial output	Better-off (n=33)	Middle (n=33)	Poor (n=54)	RMSE
Milk	7.31[a]	6.24[b]	6.34[c]	1.31
Offtake	11.06[a]	10.50[b]	10.39[c]	16.96
Manure	9.68[a]	8.93[b]	7.39[c]	5.80
Hides/wool	7.73	7.57	7.45	3.31
Traction	5.22[a]	4.40[b]	4.82[b]	08.08
LWP (USD m^{-3})	0.32	0.31	0.30	

Different superscripts [a,b,c] within a row represents significant differences at $p < 0.05$.

4.3.2 Discussion

Livestock beneficial outputs

Households use the advantage of keeping different livestock species to derive sustainable outputs and services using available resources. The current study considered outputs such as milk, offtake, manure, hides/wool and traction to estimate the annual beneficial outputs derived from livestock in each household. However, other studies like (Behnke 2010) highlight that livestock under mixed crop-livestock system in developing countries like Ethiopia perform economic and social functions which are not easily measured in monetary values. According to the findings of this study, offtake was the prime share of beneficial outputs derived from livestock followed by manure but varied among wealth groups. The variations in offtake among wealth groups was also found by Bekele et al. (2017) and Behnke (2010) who reported a low animal offtake rate in mixed farming system. On the other hand, (Kebebe et al. 2015) reported manure and traction services as one of the prime share of the annual beneficial outputs in Ethiopia. Meanwhile, Bekele et al. (2017), reported milk production followed by traction services and manure as prime beneficial outputs regardless of wealth status. Manure is very important in improving soil fertility replenishment. In the current study, manure was the second-highest beneficial output that was reported in different wealth groups followed by milk and traction. Wealthier households are possibly at an advantage of having an ability to replace traction animals due to their high numbers than poor households.

The differences in milk production among the different wealth groups is possibly due to that wealthier households are able to keep particular crossbred animals than poor farmers. Even though there is variation in milk production among the wealth groups, it contributes the least in the overall total annual outputs. However, milk production should not be undermined in this area, provided that good animal husbandry and management interventions are needed. The primary purpose of livestock keeping in a mixed farming is to maintain continuous livestock herd and compliment crop production. Bekele et al. (2017) suggests that, an increased number of livestock in an individual household could lead to increased LWP in the short term. The findings of the study also reported wool/hides as one of the annual beneficial outputs derived from livestock in the study area. This also indicates the extent of willingness and different abilities of households to keep sheep.

LWP

Although rainwater plays a significant role in livestock production, the increased scarcity of fresh water resources has raised concern about the rainwater conversion efficiency into livestock goods and services (Kebebe et al. 2015). Mean LWP did not vary significantly among different wealth groups. Better-off households had higher LWP followed by middle group then poor households. These results are surprising as better-off households are expected to obtain highest LWP than middle and poor households. In this study, wealthier households keep their livestock as standing assets than selling, while poor households sell their livestock to get cash and use other livestock products. The numerator of the LWP equation summarises the net beneficial goods and services obtained from livestock, while the grouping of the wealth categories used standing livestock and dwelling type as an index of wealth. These results suggest that being considered, as a wealthier household does not automatically mean higher LWP.A possible explanation to variations in LWP among wealth groups could be the variations in livestock household holdings, access to labour and other household assets, which was evident as wealthier households own more livestock than middle and poor households. Kebebe et al. (2015) stated that wealthier households stand an advantage for their high numbers of livestock to convert available feed to higher beneficial outputs such as milk, offtake, manure, traction and wool/hides. Results from other studies such as Kebebe et al. (2015) and Bekele et al. (2017) were used for comparison in this study, which revealed variation in mean LWP obtained in different studies among different wealth groups. On the other hand, differences in the mean LWP obtained in these studies could be linked to differences in livestock products prioritised and obtained in terms of least and most importance in the different studies. ET of 270 mm was reported in this study, which could play a major role in explaining the differences of LWP in different studies. The relatively low ET compared to annual rainfall can be explained by the low leaf area of the vegetation available to livestock. These findings suggest that households with low livestock holdings cannot sufficiently utilise feed from crop residues and grazing lands. Haileslassie et al. (2009) found that in Ethiopian highlands, most of the livestock beneficial outputs are from households who own high numbers of livestock. Variations in LWP among different wealth group categories suggest the possibilities to improve LWP with the current level of knowledge given that farmers have better access to land, labour and oxen for traction. Furthermore, our results on LWP are consistent with Haileslassie et al. (2009), who also found that better-off households and medium wealth households have higher total beneficial outputs and LWP. Although water use in cultivated lands and areas around the homesteads was not included in the analysis because of the difficulties to successfully, separate the two domains due to small gardens available in different households. This could possibly be the reason for differences in LWP among different wealth groups. For example, better-off households could have backyard gardens and be able to plant more feed for livestock than poor households are. (Kebebe et al. 2015) urges that, increased LWP is a result of increased feed efficiency utilised by the animals and increased water use efficiency through rainwater management.

4.4 Influence of *Acacia mearnsii* on grass production

Globally, grasslands are under threat from woody encroachment by IAPs such as *Acacia mearnsii* and this undermines rangeland grass production. In South Africa, clearing of black wattle invasions is occurring throughout the country to help repair ecosystems. It is important to establish the ability of landscape cleared of IAPs such as *A. mearnsii* to recover. From an ecological restoration perspective, Le Maitre et al. (2011) recognised that depending on the degree of modification, invaded landscapes may be capable of either self-regeneration or aided regeneration through biotic and abiotic interventions if critical thresholds have been surpassed in the system. Most management efforts to restore degraded land are underpinned by an appreciation of soil characteristics (Costantini et al. 2016). On the basis of this, soil indicators could be vital in assessing the degree of ecosystem or rangelands change due to IAPs. It should be observed that soils are vegetation growth substrates and provide essential nutrients that support biomass production, which is critical for the supply of ecosystem services such as forage resources (Smith et al. 2015). As such, an understanding of specific soil characteristics that are capable to be used as a prognosis of landscape recovery or deterioration is important to demonstrate landscape ability (Costantini et al. 2016). Within the broader context of IAPs clearing in South Africa, there is need to quantify herbage recovered after removal of the plants to better understand the economics of clearing from a ranching perspective. Hence, a better understanding of the dynamics in herbage or grass production over rangelands cleared of IAPs is crucial for grazing management purposes.

It has been demonstrated that the clearing of the invasive *Prosopis* (mesquite) increases grazing capacity and background species emerged in the Nama Karoo Biome of South Africa (Ndhlovu et al. 2016). In addition, reduction in the over-storey canopy on a *Colophospermum mopane* dominated savanna woodland enhanced the development of understorey vegetation such as grass in the Limpopo province of South Africa (Smit 2005). While these studies are important in showing the importance of reducing over-storey canopies to encourage undergrowth in the two biomes, the impacts of *A. mearnsii* clearing on herbage in the grassland biome of South Africa have not been adequately described. Secondly, it is useful to develop other tools that could help farmers to quantify grass biomass in areas cleared of IAPs to inform short and long-term decision-making on grazing. Hence, the development of simple and parsimonious metrics based on allometric relations could be more useful to farmers who need to quantify rangeland grass/ herbage to help in longitudinal grazing management in areas cleared of *A. mearnsii*. In this section, above-ground grass biomass, grass herbage and ANPP were used interchangeably. The aim of this section was to understand the effects of *A. mearnsii* on soil physico-chemical properties and how its clearing influenced above-ground herbage production.

4.4.1 Evaluating impact of **A. mearnsii** *invasion on abiotic soil properties and its clearance on grass herbage production*

Methods

To investigate the impact of *A. mearnsii* on abiotic soil properties, soil samples were collected across quaternary catchments S50E, T12A and T35B in the Eastern Cape. Details of study site, sampling and statistical analyses can be found in Gwate et al. (2018). To better uncover the effects of clearing of *A. mearnsii* on grass herbage production, the line transect (Flombaum and Sala 2007) and the disc pasture metre (Bransby and Tainton 1977; Zambatis et al. 2006) were used. Allometric equations developed from these two methods were used in estimating above-ground grass biomass in grasslands cleared of IAPs in the northern Eastern Cape.

Results

Multivariate tests showed that the invasion status (cleared, invaded or uninvaded), site factor and the interactive effects of the two had significant effects on the selected soil variables ($p < 0.001$) and this allowed for further analysis of the between subject effects. The invasion status had statistically significant effects on P, K, N, CEC, total cations, acid saturation and pH ($p < 0.05$) whereas marginal significant differences were detected for Mg and Zn ($p < 0.1$). The P was higher in the invaded samples compared to soils in both cleared and uninvaded areas. Highest K, CEC, N, Zn and total cations were observed in the invaded sites followed by the cleared and finally the uninvaded areas. Bulk density was lower in the cleared compared to the invaded and uninvaded sites. On the other hand, Ca, Mg and pH were highest in the uninvaded areas while acid saturation was highest in the cleared. The posthoc HSD revealed that P was significantly different in invaded and uninvaded areas ($p = 0.02$) and with respect to K, statistically differences were detected in cleared and invaded sites ($p = 0.04$). At the same time, pH ($p < 0.001$) was significantly different between the cleared and uninvaded sites while Mg ($p = 0.09$) was marginally different ($p < 0.1$) between these sites. In addition, pH ($p < 0.001$), CEC ($p < 0.001$), total cations ($p = 0.01$), acid saturation ($p = 0.006$), N ($p = 0.003$) were significantly different ($p < 0.05$) between uninvaded and invaded areas. Furthermore, CEC ($p < 0.001$), N ($p = 0.04$), acid saturation ($p = 0.004$) were significantly different between cleared and invaded sites. Finally, total cations ($p = 0.08$) and Zn ($p = 0.08$) were marginally different between cleared and invaded areas ($p < 0.1$).

The site factor had a significant effect ($p < 0.05$) on bulk density, Ca, Mg, CEC, total cations, acid saturation, pH, N, Ca and Zn while marginally significant difference ($p < 0.1$) was detected with respect to K. The interactive effects of site and invasion status had significant impact on most of the analysed soil variables ($p < 0.05$) except for bulk density. The first three axes of the PCA explained 75% of the total variation. An investigation of the communalities table revealed that the factor solution extracted much of variation in the variables since they were high (0.55 – 0.95). The first rotated component had high loadings for K, Ca, Mg, total cations and acid saturation but it was negatively correlated to acid saturation. The second component matrix was highly positively correlated to P as well as CEC and negatively correlated to pH. The third component increased with an increase in bulk density and it was negatively correlated with Zn. In order to further illuminate on the effects of invasion status on the selected soil variables a biplot can be found in Gwate (2018). Most of the uninvaded sites were highly positively correlated with soil pH while the opposite vector was dominated by invaded and cleared sites. These invaded and cleared sites had higher bulk density (D), CEC, P and acid saturation compared to the uninvaded sites. At the same time one vector indicates that cleared and invaded sites were highly correlated to Mg, Ca, K, N, Zn and total cations (Total) while the opposite vector also had a huge presence of similar cleared and invaded sites.

4.4.2 Measurement and modelling of above-ground biomass using in situ methods

Calibrating line transect

The regression slope between grass canopy cover and grass biomass was 88.5 and R^2 was 0.96 ($p < 0.001$). The regression line between dry matter and canopy cover was forced through zero because where there is no cover there is no biomass.

Calibration of the disc pasture meter

The mean DPM settling heights for sites within quaternary catchments S50E, T12A and T35B were 19.53, 16.39 and 20.93 cm respectively. Data from a burning trial on Dohne sour veld (Ndovela 2014) in the Eastern Cape was also analysed to compare with results from the present study (see Gwate 2018). The relationships between above-ground biomass and the disc settling height were highly significant ($p < 0.001$). The mean canopy cover for S50E, T12A and T35B sites were 71 (N = 7 line transects), 64 (N = 7 line transects) and 65% (N = 7 line transects) respectively. The mean canopy cover for each catchment (S50E, T12A and S50E) were used to estimate ANPP across sites using a regression equation (Gwate 2018). Based on the average combined canopy cover across the study sites, 290 g m^{-2} $year^{-1}$ of grass herbage mass was predicted in areas cleared of *A. mearnsii* in the northern Eastern Cape. With respect to DPM, the mean DPM settling heights for S50E, T12A and T35B were 19.53 (N = 36), 16.39 (N = 54) and 20.93 (N = 54) cm respectively. On the basis of these DPM settling heights and the combined grass above-ground biomass (commercial and communal area, Gwate 2018) and the Ndovela (2014) study regressions, above-ground grass biomass for each site was predicted. Tukey's HSD revealed that grass above-ground biomass for each of the three sites was statistically different ($p < 0.01$). Predicted grass above-ground biomass was 10 and 8% higher in S50E compared to T12A and T35B respectively. Based on the average DPM settling height across the sites, grass above-ground biomass of 313 g m^{-2} $year^{-1}$ was predicted for areas cleared of *A. mearnsii* in the northern Eastern Cape. Higher predicted grass ANPP for South African sites coincided with areas that received higher mean annual rainfall based on gridded data (Schulze 1997). However, sites cleared of IAPs at the lower end of the rainfall gradient like T12A yielded similar or more grass above-ground biomass than some higher rainfall sites of O'Connor (2008) and Everson and Everson (2016) studies. As was the case with the line intercept method, Tukey's HSD indicated that predicted grass above-ground biomass of each sites were statistically different ($p < 0.01$). The DPM predicted grass above-ground biomass at T12A was 17% and 22% less than that of S50E and T35B respectively. In sharp contrast with the line intercept data, grass above-ground biomass predicted at S50E was 10% less compared to that of T35B. It was only in T12A that the line intercept method predicted marginally (5%) higher grass above-ground biomass compared to the DPM method. Overall, DPM predicted 8% more ANPP than and line intercept method (see Gwate 2018).

Discussion

The invasion status impacted significantly on soil properties related to P, CEC, total cations, acid saturation and pH. Soil chemical properties related to pH greatly influenced CEC, total cations and acid saturation. When pH is low, more exchangeable cations are acidic leading to higher acid saturation and an increase in total cations. The soil acidification has implications on the ability of forage recovery after the removal of *A. mearnsii* from the rangelands. Soil fertility is strongly coupled with the ability of soil to retain and exchange nutrients. The ability of soil to attract positive cations (for example, Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) was enhanced after the invasion due to increases in CEC and total cations, suggesting that these nutrients could have become more available for production. Soils with high CEC tend to attract more positive exchangeable cations indicating high clay content (Saidi 2012). Although an increase in CEC was noted for invaded areas, the observed values were still relatively low, suggesting that the soils had a generally higher sand content and nutrient leaching was a distinct possibility (Aprile and Lorandi 2012). Such soils require less lime to correct the pH than those with CEC values greater than 6cmol L^{-1} (Edmeades 1982; Anderson et al. 2013; Portmess et al. 2014). The N content was higher in invaded compared to the uninvaded sites since it is well-established that *A. mearnsii* fixes atmospheric nitrogen and this is consistent with results from elsewhere (Moyo and Fatunbi 2010; Tye and Drake 2012; Lazzaro et al. 2014; Forrester et al. 2007). Other growth variables such as P and K were also higher in the invaded compared to the uninvaded areas and a similar pattern was observed in the Eastern Kouga Mountains, Eastern Cape (van der Waal 2009). This suggests that once *A. mearnsii* is removed, more nutrients will be available to drive grass/ herbage biomass production. Notwithstanding reactions with other minerals like P, micronutrients may not be limiting at the study sites as it is well-established that such micronutrients as zinc become less soluble as pH increases and becomes greater than 6.5 (Zhu et al. 2001). The pH in the study sites was low (< 4) and hence it promotes the solubility of zinc as shown by higher Zn content in invaded compared to the uninvaded and cleared sites.

Results suggest that background soil characteristics influence the extent to which abiotic soil characteristics are transformed by *A. mearnsii*. A better understanding of local factors will give insights into an appropriate package for successful rehabilitation where active interventions are considered. This could inform the nature and character of interventions to improve the soil conditions. The PCA results suggest that *A. mearnsii* essentially impacted physico-chemical soil characteristics by influencing properties related to growth, P availability and pH as well as soil physical properties (bulk density) coupled with micronutrients (Zn). The first principal component axis can conveniently be termed cations that affect growth qualities (K, Mg, N, and Ca), the second one, P dynamics (P and pH) and the third physical properties (bulk density) and micro nutrients (Zn). The second component is related to the influence of pH in dissolving inorganic P to become potentially available to plants since P is more soluble in more acidic soils (Devau et al. 2009). The high correlation of the second principal component with total cations and CEC is reflective of chemical reactions to dissolve inorganic P. With respect to the third component (bulk density and zinc), it is well-established that bulk density tends to increase with decreasing micronutrients (Horneck et al. 2011; Chaudhari et al. 2013) and this was consistent with results from the present study. Results indicated the clustering of sites according to invasion status, confirming that the selected soil variables had been transformed due to *A. mearnsii*. However, the simultaneous presence of sites with different invasion status could be related to the length of time lapsed after clearing. For example, the simultaneous occurrence of cleared and uninvaded sites on specific vectors of the biplot could be indicative of the rehabilitation that has occurred on the cleared sites to the extent that such sites became similar to uninvaded sites in terms of the assessed soil variables. It should be noted that IAP clearance at the study sites started circa 2005 and has been ongoing.

With respect to grass herbage, regression equations developed were similar to other studies (for example, Flombaum and Sala 2007; Ndovela 2014). The DPM data rejected the widely-held perception that grass biomass production on commercial land differs substantially from communal areas (O'Connor 2008; Palmer and Bennet 2013) since grass biomass from the two areas were similar. There was good agreement between the line intercept and DPM approaches, thus validating biomass derived. These regression equations provide an easy to use technique for non-destructively estimating grass biomass in the grassland biome in areas cleared of *A. mearnsii* to help farmers make informed grazing decisions. In addition, allometric relations developed from the DPM may be useful in determining fuel loads in this vegetation type where fire is a widely used management tool.

The above-ground grass biomass predicted across sites were similar to other estimates, albeit, in natural grasslands uninvaded by IAPs. In the Eastern Cape, Danckwerts and Trollope, (1980) found ANPP values ranging from 213 to 304 g m^{-2} $year^{-1}$ of above-ground grass biomass in *Themeda, Digitaria/ Sporobolous* spp. dominated landscapes. O'Connor (2008) found above-ground grass biomass values of 292 and 244 gm^{-2} yr^{-1} in commercial and communal rangelands of the southern Drakensberg area. Everson and Everson (2016) using long-term data estimated above-ground grass biomass values ranging from 190 g $m^{-2}yr^{-1}$for montane grassland exposed to annual winter burning to 471 g $m^{-2}year^{-1}$for grasslands exposed to two yearly burning. Further, Everson and Everson (2016) reported that very early studies in South Africa estimated above-ground grass biomass from 63 g m^{-2} $year^{-1}$ for grasslands receiving 500 mm mean annual rainfall, to 390 g m^{-2} yr^{-1} in the higher rainfall areas. The PCA soil results suggested that the selected soil variables could return to pre-invasion conditions if the landscape is cleared as shown by the simultaneous occurrence of some of the cleared and uninvaded sites in the PCA vector space. The clearing of *Acacias* was not accompanied by further biotic or abiotic interventions to rehabilitatte the soil. These soil results and the observed production rates in this study suggest that grasslands invaded by *A. mearnsii* may be capable of autogenic recovery if cleared of *Acacias*. Results of this study revealed the effect of rainfall gradient on above-ground grass biomass, with high rainfall areas coinciding with higher above-ground grass biomass compared to lower rainfall areas. However, sites cleared of IAP at the lower end of the rainfall gradient were as productive as, and even better than, some higher rainfall sites of the O'Connor (2008) and Everson and Everson (2016) study areas. This suggests that rainfall alone cannot adequately explain grassland production but other factors such as burning and grazing play a role (Koerner and Collins 2014; Everson and Everson 2016). For the sites in the present study, the high predicted above-ground grass biomass could have been due to nutrient release after the removal of *A. mearnsii*. It is well-established that *Acacias* increase fertility by symbiotic fixation of atmospheric N (for example, May and Attiwill 2003; Forrester et al. 2005; Forrester et al. 2007; Boudiaf et al. 2013; Lazzaro et al. 2014).

4.4.3 Exploring optimum management strategies for grasslands invaded

The foregoing section illustrated that *A. mearnsii* does affect abiotic soil characteristics and capacity of invaded grasslands to recover. *A. mearnsii* invasion affects ecosystem services that grasslands can provide. It should also be recognised that IAPs offer a number of beneficial services to the communities. At the same time, it has been shown that clearing may not necessarily promote regeneration of indigenous vegetation in riparian areas and re-infestation by other invaders remains a distinct possibility (Holmes et al. 2008; Le Maitre et al. 2011; Simberloff et al. 2013) especially within the purview of global fertilization by carbon under elevated atmospheric CO_2 concentrations. Van Wilgen et al. (2011) observed that where IAP eradication is impossible owing to the magnitude of the infestation, containment and impact reduction were viable strategies. Despite huge expenditure in clearing efforts in South Africa, only a small portion of infested areas have been cleared. Many studies have reported very little progress (< 10%) in some areas prioritised for clearing since the inception of the clearing programme in 1995 (Beater et al. 2008; Van Wilgen et al. 2012). We have also observed that since the inception of the clearing project in the northern Eastern Cape, there has been relatively little progress in terms of reduction in the total infestation. A preliminary assessment using recent QuickBird imagery (2000 compared to 2015) on land under communal tenure shows significant densification of existing infestations. The patches of successfully cleared lands are mainly 'low hanging fruit' situated on land under freehold tenure or on communal land with ease of access (for example, adjacent to roads and villages), and the spatial extent seldom exceeds 5 ha. In addition, there is seldom evidence of 'follow up' after the initial clearing. As a consequence, there is need for innovative strategies to expedite the clearing process or to take advantage of the invasion to enhance net benefits to the community. Opportunities include enhancing grass production for farmers and promoting the water and biodiversity benefits envisaged by the WfW programme. The aim of this section was to understand the biophysical properties of *A. mearnsii* in grasslands as they relate to grass production and to explore possible alternative management options.

Methods

Above-ground biomass (AGB) of *A. mearnsii* was predicted following Paul et al. (2013). Based on the land systems approach (Van der Merwe et al. 2015), a total of 46 sampling points were located across environmental gradients and *A. mearnsii* canopy LAI, grass cover and slope were measured. A total of 23, 15 and 8 points were located in quaternary catchments S50E, T12A and T35B respectively. The points were carefully chosen to cover diverse slope ranges and the total number of points was proportional to the size of invaded patches in each quaternary catchment. We hypothesised that a particular black wattle canopy LAI and terrain slope combination militates grass production. Details of the study sites, data collection and analysis can be found in Gwate et al. (2016c).

Results

Mean AGB was estimated at 279 ton ha^{-1} with the biggest contributor to this biomass being DBH class 3 and predicted AGB differed significantly across the three DBH classes ($p < 0.05$). Absolute total stand biomass ranged from 26 to 866 ton ha^{-1} across sites. The relationship between Normalised Difference Vegetation (NDVI) and above-ground biomass was significant. LAI and NDVI (normalised vegetation difference index) had a strong linear relationship in this study ($R^2 = 0.73$, Durbin-Watson statistic = 2.2). For details readers are referred to Gwate et al. (2016c)

LAI and grass cover had a significant relationship ($p < 0.05$) although LAI explained only about 38% of the variation in the grass cover ($R^2 = 0.4$). A regression equation was developed which gave insights into the LAI values that have to be maintained to allow viable grass production (Gwate et al. 2016). A generalised linear model using the logarithmic link function was fitted into the data. This model was found to be ideal since grass cover decreases quickly and then levels out at zero with increasing LAI. For example, to sustain a 50% grass cover in infested areas, *A. mearnsii* LAI should be maintained at about 0.72 and LAI of about 0.12 could sustain 100% grass cover. In addition, as soon as the LAI approaches 2.1, grass cover drops to about 10%. Using multiple linear regression to predict grass cover from a combination of LAI and slope, the model explained about 37% of the total variation in grass cover ($R^2 = 0.4$) and the association was statistically significant ($p < 0.05$). The relationship between the terrain slope and grass cover was weak with slope only explaining about 2.6% variation in grass cover. Slope accounted for about 18.1% variation in *A. mearnsii* LAI across the environmental gradients and this was statistically significant ($p < 0.05$).

Discussion

The adopted equation for predicting AGB is robust as it was species specific and the data used was derived in a region with similar conditions as our case study. Chave et al. (2005) recommended that including wood density and height in allometric equations resulted in more accurate AGB estimates especially in complex environments where mixed species regressions should be used. However, this study was concerned with a single species and Paul et al. (2013) recorded high model efficiency indices for equations that used DBH only, suggesting that the relationship was credible and that models using DBH only are robust in single species areas and hence, our AGB results should be accurate. Despite huge investment in clearing of IAPs in South Africa, there has been little progress (McConnachie et al. 2012; Van Wilgen et al. 2012).

The local baseline data generated in this section, when combined with GIS estimates of the spatial extent of invasion, could be vital in predicting the economic value of the resource and may give communities an opportunity to negotiate trade contracts from an informed position. Within the broader context of reducing emissions from all land uses (REALU, Kuyah et al. 2012), the effect of *A. mearnsii* on carbon sequestering can now be quantified in the selected area. Based on the strong positive relationships established in this paper, it should theoretically be possible to confidently predict *A. Mearnsii* LAI from NDVI. Although, a strong relationship was established to predict AGB from NDVI, it was only applicable over a very narrow LAI, NDVI and time range. Therefore, given that *A. mearnsii* is evergreen, it might be prudent to undertake further studies over a year to discern whether this relationship persists throughout the year. Other studies have found that LAI and NDVI were useful predictors of biomass before saturation point is reached (Ghebremicael et al. 2004; Wessels et al. 2006; Reddersen et al. 2014).We did not observe any NDVI saturation in this study. Further, the seasonal summation of NDVI (∑NDVI) has often been found to correlate very well with biomass and several studies have used it as a proxy for AGB (for example, Fensholt et al.

2013; Dardel et al. 2014). Although terrain slope accounted for only 18.1% of the total variation in *A. mearnsii* LAI, the relationship was significant and this was indicative of water availability at plant root zones. This was not surprising since it is expected that water should be more available in gently sloping areas as it collects at such points from the steep slopes.

Managing *A. mearnsii* invaded rangelands

The use of a landscape based sampling technique informed by terrain slope ensured that diverse landscapes were covered to investigate the potential for grass production in *A. mearnsii* infested areas such that results are not coloured by local physical landscape factors such as nutrients, aspect, runoff and run-on dynamics. From the sampling conducted (terrain slope ranging from 3.2º to 26.1º), slope was not a constraint to grass production. This was confirmed statistically that the relationship between terrain slope and grass cover was weak and insignificant. Hence, the data rejected our preliminary hypothesis that at critical terrain slope and *A. mearnsii* LAI thresholds, grass production was inhibited. Combining slope and *A. mearnsii* LAI to predict grass cover did not improve the model. This means that LAI was more influential in determining grass production than terrain slope.

Results from this study suggest that as soon as canopy LAI approaches 2.1, grass cover drops to about 10% and maintaining a canopy LAI of 0.72 will make about 50% more grass cover available for grazers. This was consistent with results by Ansley et al. (2013) who found that maintaining woody cover below 30% enhanced growth of productive C_4 grasses. Therefore, from a grazing perspective, it is possible for grass production to be viable in *A. mearnsii* invaded areas. In order to promote grass production, it will be essential to reduce LAI of *A. mearnsii* through ecological thinning. Ecological thinning is the selective removal of stems in woody ecosystems to restore historical or ecologically desirable ecosystem structure and processes (Dwyer et al. 2010). It is well-established that *A. mearnsii* has allelopathic effects (Fatunbi et al. 2009) hence thinning could help to reduce these and subsequently, it may promote multiple ecosystem services such as grass production and carbon sequestration by the woody *A. mearnsii* among others. Ecological thinning as a management approach could link very well with the 'novel ecosystem' paradigm. It can be postulated that the IAP invasions in socio-ecological conditions reported in this paper have transformed the landscape into a 'novel ecosystem'. In a context of global environmental changes associated with climate change, ecological restoration of such rangelands could be very difficult (Estell et al. 2012). Therefore, when it is no longer socially, economically and ecologically possible to restore an ecosystem, it is prudent to explore alternative targets that will inadvertently deliver requisite ecosystem services (Monaco et al. 2012). From this perspective, embracing the 'novel ecosystems' approach may be a viable strategy to salvage value from transformed rangelands. About 70 Australian *Acacia* species have been introduced in South Africa since 1830s (Van Wilgen et al. 2011) and most of them have increasingly become invasive. Therefore, it may be pragmatic to embrace the 'novel ecosystem' paradigm to the management of IAPs such as Australian *Acacias*. Coffman et al. (2014) found that shrub clearing as a form of restoring grasslands in the Chihuahuan Desert did not restore the ecosystem but produced a 'novel ecosystem'. Therefore, there is a distinct possibility that such a response may occur in other grasslands, hence entrenching the need for adopting this new paradigm. However, some scientists are very sceptical of the 'novel ecosystems' approach since they believe it encourages poor environmental management (for example, Simberloff et al. 2013; Murcia et al. 2014). Nevertheless, the 'novel ecosystems' paradigm does not discount traditional approaches such as ecological restoration and rehabilitation but strives for an appropriate mix of old and emerging approaches (Hobbs, Higgs and Harris 2009, 2014). Therefore, it is consistent with the adaptive management approach for intractable problems and may be worth embracing with respect to management of IAPs.

4.5 Comparison of remotely-sensed NPP and remotely-sensed ET per land cover class

4.5.1 MODIS NPP and ET per land cover class

NPP (MOD17A3, version 5, 1km) (Running and Mu 2015) and ET (MOD16A2, version 5, 1km) (Mu et al. 2007; Mu et al. 2011) products, were extracted to represent carbon and water fluxes respectively. Gwate et al. (2018c) investigated the influence of land cover change on AET using measured values and MOD16A3 data in catchment S50E.

4.5.2 Methods

Annual NPP (MOD17A3) and ET (MOD16A2) were extracted for the period 2000 to 2014 to visualise the trend of these variables in the catchments. Non-parametric loess regression was used to fit a loess curve. Mean NPP and ET per pixel were calculated. Using a zonal statistics method (extract in R) summary statistics were computed for each land cover transition class from the gridded datasets.

4.5.3 Results and discussion

A boxplot of annual NPP for the study period is shown in Figure 4.1a, b and c for the three catchments T12A, T35B and S50E respectively. Rainfall from weather stations, WS 30388 – Cala, representing the lower catchments T12A and S50E, and WS 30610 – Maclear: Somerton, can be seen in Figure 4.1d. The linear trend is shown with a dotted line while the loess curve indicates the local trend.

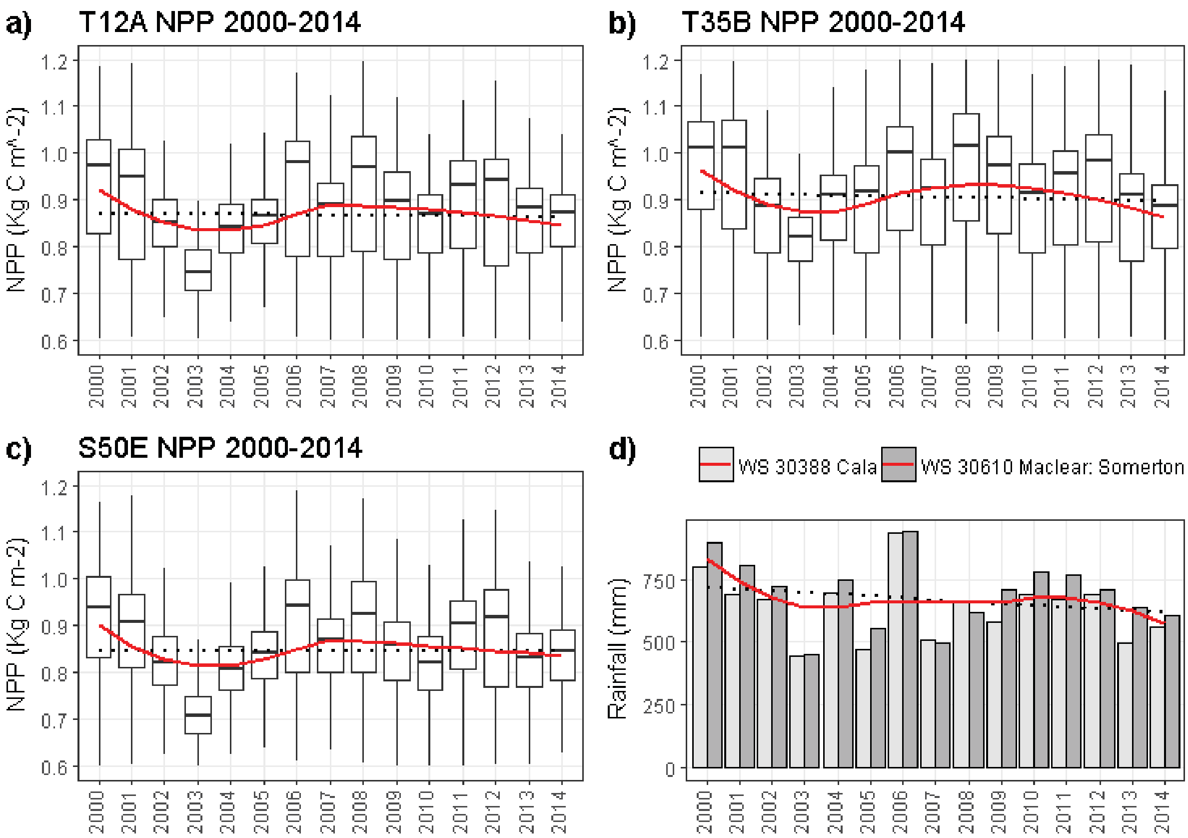

Figure 4.1 Mean annual NPP values for a) T35B, b) T12A and c) S50E, with rainfall in d) Loess regression curve in red, linear regression curve in dotted lines.

NPP in T35B has the highest mean value of 0.892 $kgCm^{-2}$, compared to 0.849 $kgCm^{-2}$ in T12A and 0.802 $kgCm^{-2}$ in S50E. The trend is strongly related to that of the rainfall pattern and this is consistent with results from section4.4 of this report. Some anomalies were noted, in that despite average increasing rainfall from 2009 to 2011, NPP values dropped in S50E and T12A in 2010.

Similarly, Figure 4.2a, b and c depict the annual ET over the 15-year period extracted from MOD16A2. The purpose of the boxplots is to present the large variation in the ET values at each time step and demonstrate similar trends as described for AET by Gwate et al. (2018c).

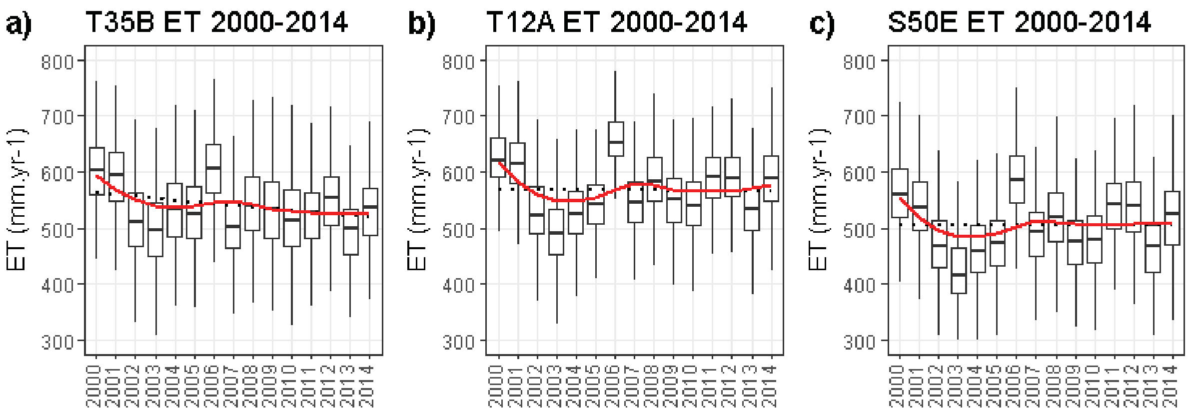

Figure 4.2 Mean annual values of NPP (a-T35B, b-T12A, c-S50E) and ET (d-T35B, e-T12A, f-S50E) per catchment over study period.

At catchment scale, there is a strong relationship between ET and rainfall and lower ET was noted for 2003 in all three catchments confirming the inflection point in 2004 indicated by Gwate et al. (2018c). Highest mean ET was computed for T12A (570 mm yr^{-1}), followed by T35B (542 mm yr^{-1}), with S50E having the lowest mean value of 508 mm yr^{-1}. The loess curve (in red) indicates the trend, though not significant ($p>0.05$) in any of the catchments.

Based on MOD17A3, Figure 4.3 draws a comparison between NPP in these land cover classes. It was noted that in all land covers, the NPP for T35B is higher, followed by T12A and S50E. This is not the case with ET (Table 4.3) where T12A shows the highest values in all classes except forest plantation (FP). However, towards 2014, there is a significant increase in ET in T12A while the NPP drops for the FP class. For comparison with Gwate et al. (2018c), Table 4.4 reports on the difference in ET modelled by MOD16A2 in grassland (UG), urban / built-up (UrBu), forest indigenous, thicket bushlands, bush clumps, high fynbos (FITBs), FP and cultivated lands (CLs) in all three catchments.

In contrast to Gwate et al. (2018c), the ET for UG prior to 2003 is higher in Figure 4.4a. This may be ascribed to the different methods used to extract values from land cover maps with potential uncertainty, especially for UG, a large dormant class. The importance of the accuracy of land cover maps is recognised, as land cover is frequently used to extract values for socio-economic and physical processes (Estes et al. 2018; Verburg, Neumann and Nol 2011). Reliability of downstream analyses can be impacted with substantial risk of error magnification (Kuemmerle et al. 2013).

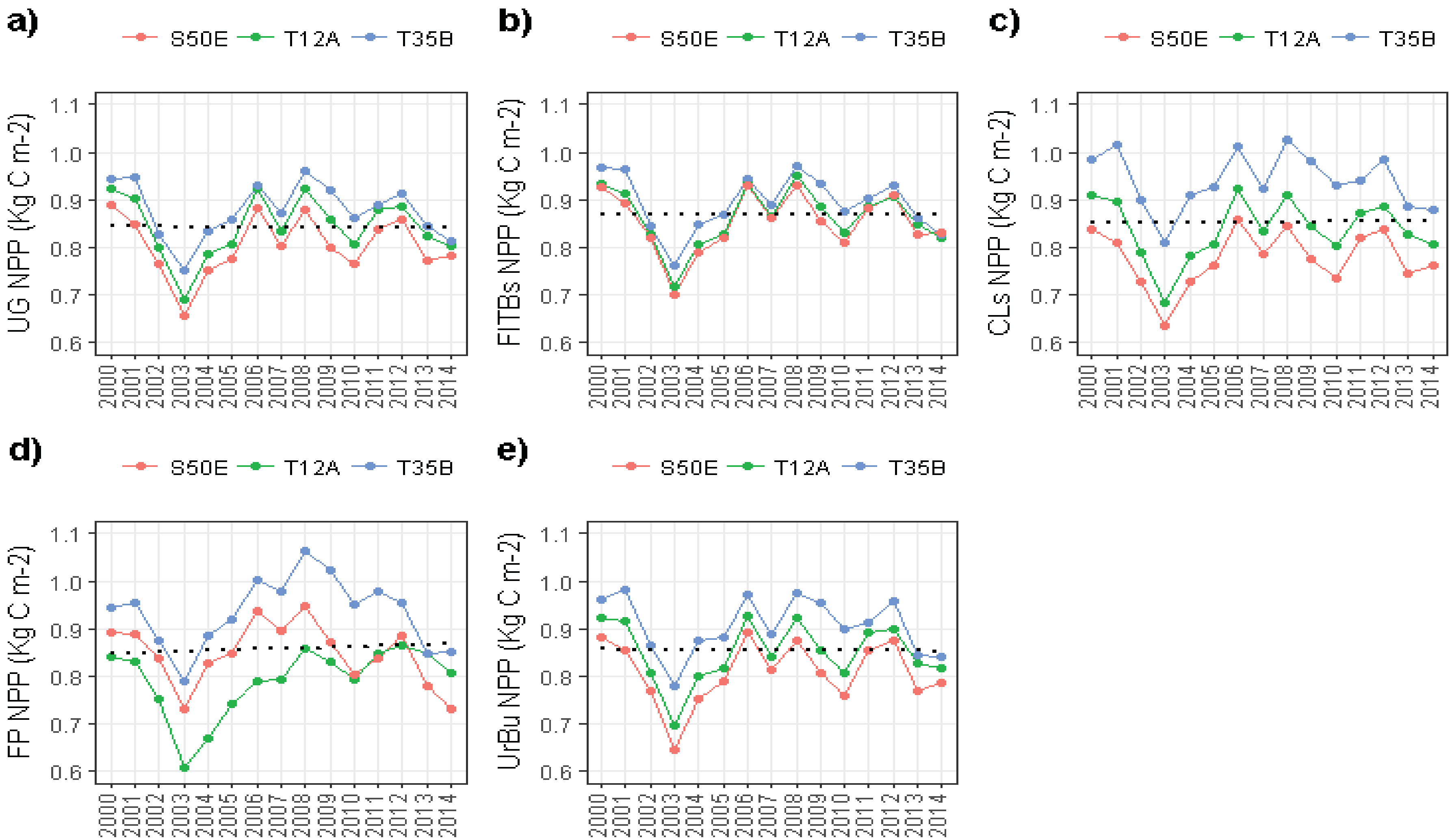

Figure 4.3 NPP time series for different land cover classes a) UG – grassland, b) FITBs – forest, c) CLs – cultivated, d) FP – plantation, and e) UrBu – Built-up

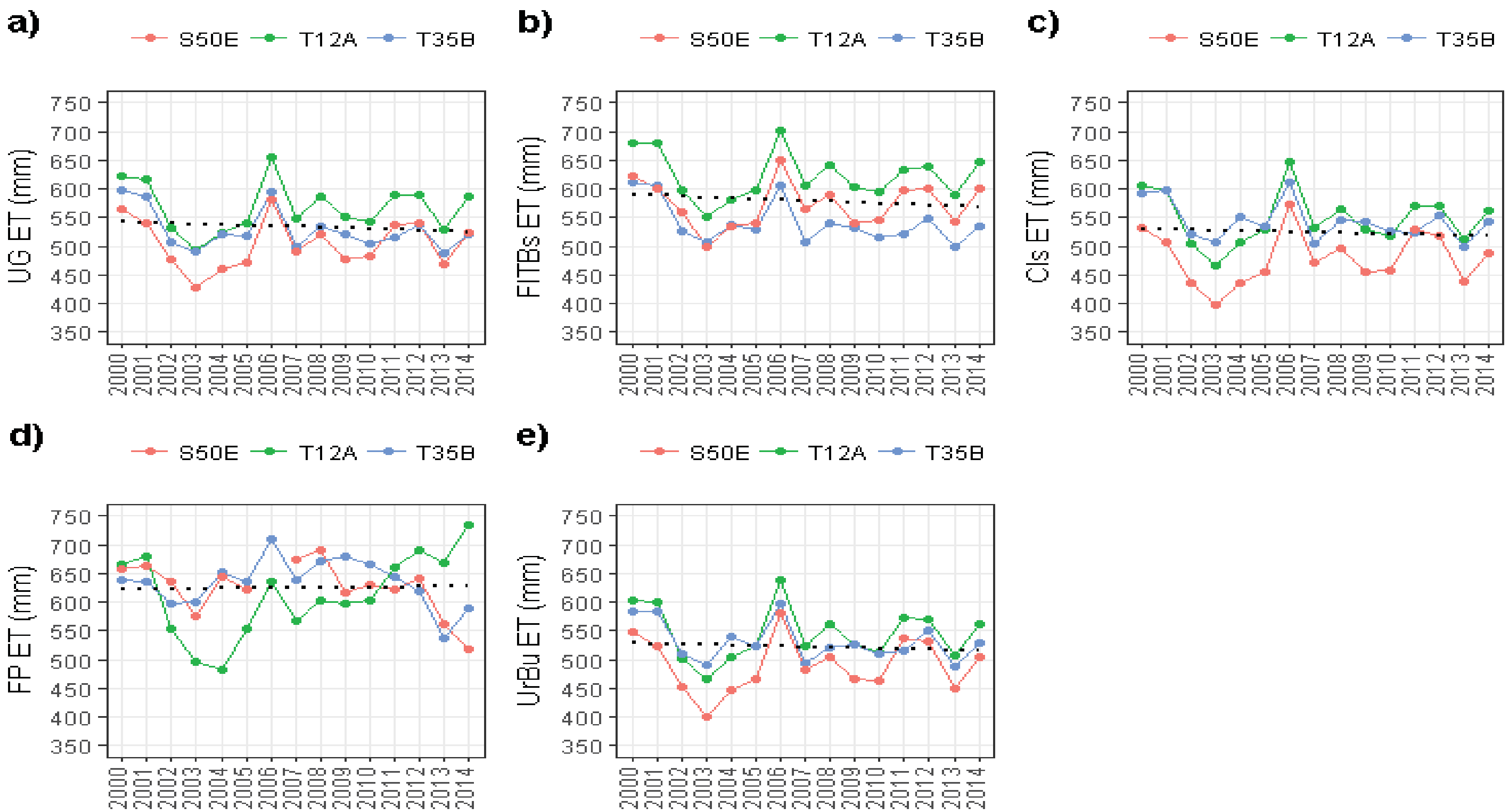

Figure 4.4 ET time series for different land cover classes a) UG – grassland, b) FITBs – forest, c) CLs – cultivated, d) FP – plantation, and e) UrBu – Built-up

Table 4.2, Table 4.3 and Table 4.4 show mean values for NPP and ET extracted for the land cover classes and organised in the form of the conversion matrix values for land cover trajectoriespresented in Münch et al. (2017). Net carbon ($x10^6$ kg) and water use ($x10^6$ m^3) derived from NPP and ET respectively are reflected in brackets next to the mean. The purpose of these values are to show the effect of the change on the carbon and water flux in the catchments. The calculation was based on the land cover class transition observed between T1-2000 and T2-2014 (Okoye 2016). Values calculated for 2014 land cover classes are given in columns and in rows for 2000 land cover classes. All values related to NPP are italicised in the tables and appear above ET for the particular class. Persistent classes are discernible on the diagonal of Table 4.2, marked with light grey (land cover change [LCC] labels P+Pf+Pu). Important transitions in this study were identified as alien invasian (If), conversion to agriculture (Ia) and urban intensification (Iu). These transitions are highlighted in Table 4.2, Table 4.3 and Table 4.4 in shades of grey from light (If) to dark (Iu) while Reclamation (Re) is emphasised in light orange.

Note that for Table 4.8, Table 4.9 and Table 4.10, mean values extracted for the respective NPP and ET time series were used to calculate carbon storage and water use. This resulted in modelled carbon storage of 1.8, 1.5 and 2.4 $x10^6$ kg carbon for the area of persistent UG in S50E, T12A and T35B respectively. It was found that the mean value for the time series was in many cases higher than the extracted value for the final time step (2014). For example, in S50E, this translated to a modelled NPP of 2.2 $x10^6$ kg carbon for UG in 2000 from mean, 0.2 $x10^6$ kg carbon higher compared to the value extracted from MOD17A3. Similarly modelled NPP for 2014 was 2.1 $x10^6$ kg, while the extracted value was much lower at 1.8 $x10^6$ kg carbon.

Table 4.2 NPP and ET for S50E based on mean value per land cover class transition with 2014 in columns and 2000 in rows. NPP values are specified in *italics* as mean in *kg C m*$^{-2}$ with carbon storage in brackets (*x10*^{6} *kg carbon*); ET is given in mm with water use in brackets (x10^{6} m^{3}). Values for persistence are highlighted in palest grey (on the diagonal) while values for transitions (If-woody intensification), (Ia-agricultural expansion) and (Iu-urban expansion) are highlighted in darker shades of grey from light (If) to darkest (Iu). Reclamation (Re) is emphasised in light orange. Land cover class abbreviations are defined in Table 4.5.

		2014								2000
2000		UG	FITBs	BRS	Wb	WI	CLs	FP	UrBu	Total
UG	NPP	0.803 (1.813)	0.82 (0.096)	0.782 (0.003)	0.412 (0.001)	0.809 (0.002)	0.777 (0.122)	0.836 (0.002)	0.795 (0.161)	2.201
	ET	504 (1.138)	529 (0.062)	480 (0.002)	329 (0.001)	505 (0.001)	476 (0.075)	599 (0.002)	482 (0.097)	1.378
FITBs	NPP	0.797 (0.111)	0.853 (0.222)	0.77 (0)	0.596 (0.001)	0.952 (0)	0.81 (0.006)	0.779 (0.005)	0.812 (0.014)	0.360
	ET	507 (0.071)	572 (0.149)	473 (0)	447 (0)	572 (0)	495 (0.004)	618 (0.004)	511 (0.009)	0.237
BRS	NPP	0.818 (0.001)	0.843 (0)	0.849 (0)			0.883 (0)	0.73 (0)	0.814 (0)	0.001
	ET	474 (0)	556 (0)	483 (0)			549 (0)	615 (0)	585 (0)	0.001
Wb	NPP	0.49 (0.004)	0.632 (0.001)		0.41 (0.051)		0.33 (0.002)		0.703 (0)	0.057
	ET	381 (0.003)	457 (0)		398 (0.049)		266 (0.001)		496 (0)	0.054

Table 4.2 (cont.)

		2014								2000
2000		UG	FITBs	BRS	Wb	WI	CLs	FP	UrBu	Total
WI	NPP	0.87 (0.009)	0.836 (0)			0.869 (0)	0.775 (0.006)		0.798 (0)	0.016
	ET	526 (0.005)	579 (0)			517 (0)	480 (0.004)		470 (0)	0.010
CLs	NPP	0.833 (0.057)	0.82 (0.017)	0.803 (0)	0.332 (0)	0.911 (0)	0.773 (0.48)		0.818 (0.013)	0.568
	ET	493 (0.034)	502 (0.01)	469 (0)	375 (0)	534 (0)	477 (0.297)		480 (0.008)	0.349
FP	NPP	0.96 (0.056)	0.914 (0.065)	1.153 (0.001)	0.595 (0)	1.123 (0)	0.904 (0)	0.846 (0.061)	0.884 (0)	0.183
	ET	646 (0.037)	683 (0.049)	624 (0.001)	503 (0)	759 (0)	584 (0)	634 (0.046)	580 (0)	0.133
UrBu	NPP	0.826 (0.003)	0.797 (0.001)	0.805 (0)			0.787 (0.01)	0.754 (0)	0.805 (0.15)	0.165
	ET	484 (0.002)	506 (0)	464 (0)			482 (0.006)	616 (0)	489 (0.091)	0.100
2014	NPP	2.054	0.401	0.005	0.053	0.003	0.627	0.068	0.339	3.551
Total	ET	1.290	0.271	0.003	0.051	0.002	0.387	0.051	0.206	2.261

Table 4.3 NPP and ET for T12A based on mean value per land cover class transition with 2014 in columns and 2000 in rows. NPP values are specified in *italics* as mean in *kg C* m^{-2} with carbon storage in brackets (*x*10^6 *kg carbon*); ET is given in mm with water use in brackets (x10^6 m^3). Values for persistence are highlighted in palest grey (on the diagonal) while values for transitions (If-woody intensification), (Ia-agricultural expansion) and (Iu-urban expansion) are highlighted in darker shades of grey from light (If) to darkest (Iu). Reclamation (Re) is emphasised in light orange. Other land cover class abbreviations are defined in Table 4.5.

		2014								2000
2000		UG	FITBs	BRS	Wb	Wl	CLs	FP	UrBu	Total
UG	NPP	0.843 (1.489)	0.83 (0.097)	0.776 (0.002)	0.959 (0)	0.814 (0)	0.831 (0.061)	0.734 (0.003)	0.833 (0.109)	1.762
	ET	567 (1.002)	585 (0.068)	516 (0.001)	607 (0)	538 (0)	548 (0.04)	608 (0.003)	543 (0.071)	1.185
FITBs	NPP	0.865 (0.065)	0.864 (0.163)			0.787 (0)	0.903 (0.005)	0.778 (0.001)	0.872 (0.003)	0.237
	ET	594 (0.045)	623 (0.118)			547 (0)	590 (0.003)	584 (0.001)	581 (0.002)	0.168
BRS	NPP	0.848 (0)	1.025 (0)						0.603 (0)	0.000
	ET	546 (0)	621 (0)						507 (0)	0.000
Wb	NPP	0.947 (0)			0.959 (0)					0.000
	ET	588 (0)			607 (0)					0.000
Wl	NPP	0.906 (0.001)	0.8 (0)		0 (0)	0.863 (0)	0.818 (0)			0.001
	ET	574 (0.001)	606 (0)		607 (0)	534 (0)	532 (0)			0.001

Table 4.3 (cont.)

		2014								2000
2000		UG	FITBs	BRS	Wb	Wl	CLs	FP	UrBu	Total
CLs	NPP	0.837 (0.037)	0.86 (0.006)	0.859 (0)		0.873 (0)	0.837 (0.138)		0.842 (0.019)	0.202
	ET	544 (0.024)	560 (0.004)	546 (0)		531 (0)	548 (0.091)		541 (0.012)	0.131
FP	NPP	1.036 (0.014)	1.127 (0.025)					0.8 (0.003)	1.015 (0)	0.042
	ET	694 (0.009)	733 (0.016)					614 (0.002)	663 (0)	0.028
UrBu	NPP	0.838 (0.01)	0.887 (0.001)	0.86 (0)		0 (0)	0.755 (0.007)		0.852 (0.097)	0.115
	ET	544 (0.006)	579 (0.001)	528 (0)		565 (0)	533 (0.005)		545 (0.062)	0.074
2014	NPP	1.617	0.293	0.002	0.000	0.001	0.211	0.007	0.229	2.360
Total	ET	1.087	0.207	0.001	0.000	0.000	0.139	0.006	0.148	1.589

Table 4.4 NPP and ET for T35B based on mean value per land cover class transition with 2014 in columns and 2000 in rows. NPP values are specified in *italics* as mean in *kg C* m^{-2} with carbon storage in brackets (*x*10^6 *kg carbon*); ET is given in mm with water use in brackets (x10^6 m^3). Values for persistence are highlighted in palest grey (on the diagonal) while values for transitions (If-woody intensification), (Ia-agricultural expansion) and (Iu-urban expansion) are highlighted in darker shades of grey from light (If) to darkest (Iu). Reclamation (Re) is emphasised in light orange. Other land cover class abbreviations are defined in Table 4.5.

		2014								2000
2000		UG	FITBs	BRS	Wb	Wl	CLs	FP	UrBu	Total
UG	NPP	0.877 (2.418)	0.916 (0.081)	0.875 (0.005)	0.975 (0)	0.948 (0.015)	0.929 (0.038)	0.92 (0.077)	0.939 (0.002)	2.637
	ET	529 (1.458)	561 (0.05)	512 (0.003)	590 (0)	572 (0.009)	533 (0.022)	606 (0.051)	536 (0.001)	1.593
FITBs	NPP	0.875 (0.21)	0.889 (0.061)	0.975 (0)	0.976 (0)	0.964 (0.002)	0.95 (0.009)	0.843 (0.008)	0.92 (0.002)	0.292
	ET	527 (0.127)	541 (0.037)	555 (0)	511 (0)	557 (0.001)	539 (0.005)	611 (0.006)	521 (0.001)	0.177
BRS	NPP	1.088 (0)					0.907 (0)	0.772 (0)		0.000
	ET	645 (0)					527 (0)	681 (0)		0.000
Wb	NPP	0.913 (0.001)	0.861 (0)	0 (0)	0.831 (0)	0 (0)	0.922 (0)	0 (0)		0.002
	ET	569 (0.001)	471 (0)	549 (0)	503 (0)	529 (0)	548 (0)	629 (0)		0.002

Table 4.4 (cont.)

		2014								2000
2000		UG	FITBs	BRS	Wb	WI	CLs	FP	UrBu	Total
WI	NPP	1.001 (0.076)	0.998 (0.001)		0 (0)	0.996 (0.018)	0.956 (0.012)	0 (0)	1.068 (0)	0.107
	ET	586 (0.044)	587 (0)		567 (0)	591 (0.011)	549 (0.007)	639 (0.009)	615 (0)	0.072
CLs	NPP	0.968 (0.048)	0.982 (0.002)	0.864 (0)	0.847 (0)	0.98 (0.006)	0.942 (0.167)	0 (0)	0.967 (0.001)	0.224
	ET	558 (0.028)	552 (0.001)	482 (0)	485 (0)	573 (0.004)	544 (0.097)	596 (0.003)	548 (0)	0.133
FP	NPP	0.948 (0.034)	0.9 (0)	1.073 (0)		0.983 (0.004)	1.023 (0.001)	0.936 (0.202)	0.851 (0)	0.241
	ET	617 (0.022)	583 (0)	642 (0)		641 (0.003)	581 (0.001)	635 (0.137)	571 (0)	0.162
UrBu	NPP	0.907 (0.003)	0.925 (0)		0 (0)	0 (0)	0.953 (0.002)	0.912 (0)	0.924 (0.003)	0.008
	ET	521 (0.002)	521 (0)		632 (0)	584 (0)	549 (0.001)	478 (0)	532 (0.001)	0.005
2014	NPP	2.790	0.145	0.006	0.001	0.045	0.230	0.287	0.007	3.511
Total	ET	1.681	0.088	0.003	0.001	0.027	0.133	0.205	0.004	2.143

4.6 Land use comparison

Land cover is the observed biophysical cover on the Earth's surface whereas land use documents the arrangements, activities and inputs people undertake in a certain land cover type to produce, change or maintain it. Increased modification of the Earth's surface through anthropogenic or natural action is reflected in the land cover (Lambin et al. 2003). It is therefore essential to have an accurate understanding of the nature and distribution of land cover to fully understand the socio-economic and physical processes that interact in the landscape (Verburg et al. 2011). Land use and land cover change (LULCC) is the result of complex interactions between humans and the physical environment (Pielke et al. 2011) described by conversion of different land use types. Detecting and characterising change over time is the natural first step toward identifying the drivers of change and understanding the change mechanism (Verbesselt et al. 2010) and its future influence. Remote sensing (RS) and GIS are essential tools in obtaining accurate and timely spatial land cover data (Foody et al. 2013), as well as analysing the changes in a study area (Münch et al. 2017; Okoye 2016).

This section provides an overview of the development of accurate land cover maps (1) from existing land cover products (Van den Berg et al. 2008) and (2) by classification of Landsat 8 data (Okoye 2016).

4.6.1 Methods

The three designated quaternary catchments (T35B, T12A and S50E) are situated in the Mzimvubu-Tsitsikamma Water Management Area in the Eastern Cape of South Africa, with a strong focus on the freehold and communal farming sectors. Details of the study sites were presented in (Okoye 2016; Münch et al. 2017). Object-based image analysis (OBIA) was used for supervised classification of the satellite imagery with a decision tree classifier (Blaschke 2010). Post-classification change analysis was performed for the varied landscape. Two frameworks were implemented for change analysis to delineate land cover change trajectories: intensity analysis (Aldwaik and Pontius 2012; Pontius et al. 2013) and an indicator-based approach (Benini et al. 2010; Feranec et al. 2010).

To compare the land use in the study area, important LCC trajectories were delineated and scenarios developed of possible change. These were used in modelling future land cover in 2030 (section 4.7).

Land cover classification

Land cover maps were derived for two time steps (T1 and T2). The first time step (T1) was selected to describe the landscape in 2000. This date corresponds to the launch of the MODIS satellites (Terra and Aqua) (Justice et al. 2002), used in other modelling and comparison studies in this project; and the South African National Land Cover (NLC) dataset (Van den Berg et al. 2008), commonly applied in studies requiring land cover as input (Van den Berg, Kotzé and Beukes 2013; Jewitt et al. 2015). A low overall accuracy (65.8%) of the selected T1 dataset (Van den Berg et al. 2008) was reported. Due to the low reported overall accuracy of this NLC dataset, it was systematically updated using a revised legend (Table 4.5) with aggregated land cover (LC) classes, subsequently referred to as T1-2000. Various steps were taken to complete the image processing to generate the land cover dataset for T2-2014 using a revised land cover legend comprising eight classes (see Münch et al. 2017; Okoye 2016). Various steps were taken to complete the image processing to generate the land cover dataset for T2-2014 using a revised land cover legend comprising eight classes (Table 4.5).

Table 4.5 Comparative land cover classification systems (LCCS)

T2-2014 class	T1-2000 class	Conceptual class*
Unimproved grassland UG	Degraded Unimproved Grassland Unimproved Grassland Shrubland and Low Fynbos	Natural and semi-natural terrestrial primarily vegetated areas
Forest indigenous FITBs	Forest (indigenous) Thicket, Bushland, Bush Clumps, High Fynbos	
Bare rock and soil BRS	Bare rock and soil (natural) Mines and quarries	Natural, terrestrial non-vegetated bare areas
Cultivation lands CLs	Cultivated, permanent, commercial, irrigated Cultivated, temporary, commercial, dryland Cultivated, temporary, subsistence, dryland	Cultivated and managed terrestrial primarily vegetated areas
Forest plantations FP	Forest plantations	
Urban / built-up UrBu	Urban / Built-up (residential, formal township)	Artificial, terrestrial primarily non-vegetated areas
Waterbodies Wb	Waterbodies	Natural or artificial primarily non-vegetated aquatic or regularly flooded water bodies
Wetlands Wl	Wetlands	Natural and semi-natural aquatic or regularly flooded vegetated areas

* Chief Directorate National Geospatial Information (CD: NGI) hierarchical structure (Lück and Diemer 2008).

The process of land cover classification and editing produced two datasets with overall accuracy of 84% and 85% for T1-2000 and T2-2014 respectively (Münch et al. 2017). The land cover classification and land cover editing are described in detail in Okoye (2016) and Münch et al. (2017).

Land cover change analysis

To assess the dynamics of land cover change in the study area, a comparison was made between the derived dataset T2-2014 and the reference T1-2000 by overlaying the two land cover maps. A square transition matrix was created where rows show the classes from T1-2000 while columns show the same classes from T2-2014 and the table entry indicates the size of the class at the intersection created by the overlay of the successive land cover maps (T1-2000 and T2-2014). Two frameworks were applied to analyse the changes. The first was intensity analysis (Aldwaik and Pontius 2012, 2013) which compares the intensity of change between land cover classes to uniform change following a mathematical approach. The second framework comprised an indicator-based approach suggested by Benini et al. (2010) where a land cover conversion label was assigned to each change intersection to allow thematic representation of the spatial distribution of changes. Readers are referred to Münch et al. (2017) and Okoye (2016).

4.6.2 Results and discussion

After overlaying the land cover maps for T1-2000 and T2-2014, the area and class-cover percentage was calculated and is presented in Table 4.6 for T35B, T12A and S50E.

Table 4.6 Comparison of land cover class areas and percentages for 2000 and 2014.

LC class	T35B				T12A				S50E			
	2000		2014		2000		2014		2000		2014	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Natural / Semi-natural (Vegetation) Cover												
UG	29 912	75.6	31 607	79.9	20 948	75.2	19 007	68.2	27 510	61.5	25 354	56.7
FITBs	3 306	8.4	1 599	4.0	2 733	9.8	3 450	12.4	4 328	9.7	4 812	10.8
BRS	3	0.0	65	0.2	3	0.0	43	0.2	13	0.0	85	0.2
Wb	33	0.1	17	0.0	1	0.0	1	0.0	1 368	3.1	1 301	2.9
Wl	1 220	3.1	463	1.2	14	0.1	17	0.1	193	0.4	57	0.1
Land Use												
CLs	2 417	6.1	2 444	6.2	2 403	8.6	2 537	9.1	7 269	16.2	8 108	18.1
FP	2 566	6.5	3 275	8.3	397	1.4	95	0.3	2 028	4.5	806	1.8
UrBu	91	0.2	77	0.2	1 365	4.9	2 716	9.7	2 050	4.6	4 237	9.5
TOTAL	39 547	100	39 547	100	27 866	100	27 866	100	44 759	100	44 759	100

In all three catchments there is an increase in cultivated agriculture, with the largest increase noted in S50E. T35B showed an increase in FP with a reduction in indigenous or alien forests (FITBs). This land cover class includes alien plants and thickets and shows an increase on low-lying, rolling flatlands and agrarian regions in S50E and T12A. Urban intensification is visible in S50E and T12A, but seems to have decreased in T35B. Wetlands have decreased significantly in T35B which may be indicative of an error in the T1-2000 dataset, reflecting different frameworks adopted for wetland identification and classification; or demonstrate a natural dynamic dependent on precipitation.

Intensity analysis approach

Intensity analysis was applied at three levels: interval, category or class and transition. The conversion matrix presented in Table 4.7 shows land cover transformation between 2000 and 2014 analysing interval and category change. The entry in the extreme lower right (highlighted) for each catchment, indicates the interval level change as a percentage of the study area. At category level, the diagonal entries (underlined) indicate persistence, which dominates most landscapes. The bottom row shows the quantity gained for each class and the right-hand column shows the quantity lost for each class. The gains are the differences between the column totals and persistence. The losses are the differences between row totals and persistence.

Table 4.7 Conversion matrix demonstrating interval level and category level change percentages (persistence on the main diagonal, underlined)

T35B		**2014**								**2000**	
		UG	FITBs	BRS	Wb	Wl	CLs	FP	UrBu	Total	Loss
2000	UG	69.7	2.2	0.1	0.0	0.4	1.0	2.1	0.1	75.6	6.0
	FITBs	6.1	1.7	0.0	0.0	0.1	0.2	0.2	0.0	8.4	6.6
	BRS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Wb	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
	Wl	1.9	0.0	0.0	0.0	0.5	0.3	0.3	0.0	3.1	2.6
	CLs	1.3	0.1	0.0	0.0	0.2	4.5	0.1	0.0	6.1	1.6
	FP	0.9	0.0	0.0	0.0	0.1	0.0	5.4	0.0	6.5	1.0
	UrBu	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.2	0.2
2014	Total	79.9	4.0	0.2	0.0	1.2	6.2	8.3	0.2	100	
	Gain	10.2	2.3	0.2	0.0	0.7	1.7	2.8	0.1		
	T35B TOTAL CHANGE										**18.1**
T12A		**2014**								**2000**	
		UG	FITBs	BRS	Wb	Wl	CLs	FP	UrBu	Total	Loss
2000	UG	63.3	4.2	0.1	0.0	0.0	2.6	0.2	4.8	75.2	11.8
	FITBs	2.3	7.1	0.0	0.0	0.0	0.2	0.0	0.1	9.8	2.7
	BRS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Wb	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Wl	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
	CLs	1.6	0.3	0.0	0.0	0.0	6.0	0.0	0.8	8.6	2.6
	FP	0.5	0.8	0.0	0.0	0.0	0.0	0.1	0.0	1.4	1.3
	UrBu	0.4	0.0	0.0	0.0	0.0	0.4	0.0	4.1	4.9	0.8
2014	Total	68.2	12.4	0.2	0.0	0.1	9.1	0.3	9.7	100	
	Gain	4.9	5.3	0.2	0.0	0.1	3.1	0.2	5.7		
T12A TOTAL CHANGE											**19.3**
S50E		**2014**								**2000**	
		UG	FITBs	BRS	Wb	Wl	CLs	FP	UrBu	Total	Loss
2000	UG	50.5	2.6	0.1	0.1	0.1	3.5	0.1	4.5	61.5	10.9
	FITBs	2.8	6.1	0.0	0.0	0.0	0.1	0.1	0.4	9.7	3.5
	BRS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Wb	0.1	0.0	0.0	2.8	0.0	0.1	0.0	0.0	3.1	0.2
	Wl	0.2	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.4	0.4
	CLs	1.5	0.4	0.0	0.0	0.0	13.9	0.0	0.3	16.2	2.3
	FP	1.3	1.6	0.0	0.0	0.0	0.0	1.6	0.0	4.5	2.9
	UrBu	0.1	0.0	0.0	0.0	0.0	0.2	0.0	4.2	4.6	0.4
2014	Total	56.6	10.8	0.2	2.9	0.1	18.1	1.8	9.5	100	
	Gain	6.1	4.6	0.2	0.1	0.1	4.2	0.2	5.2		
S50E TOTAL CHANGE											**20.7**

The category gain and loss values shown in Table 4.7 are shown graphically in Figure 4.5b alongside the change budget (Figure 4.5a) that allocates the total change to quantity, exchange and shift disagreement.

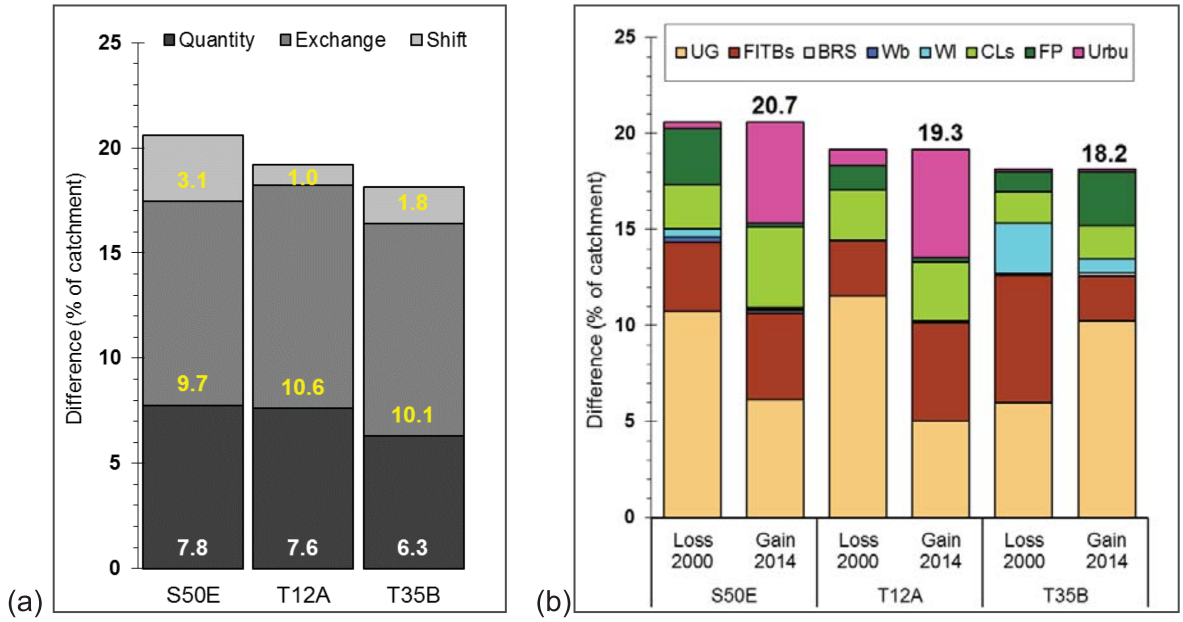

Figure 4.5 a) Change budget and b) Category level gains and losses summed to interval level loss per catchment.

Gain and loss per category were summed to obtain the interval level loss per catchment of approximately 20% over the three catchments. This amounts to a uniform change of 1.4% per year of the study period. Quantity difference (Figure 4.5a) shows the difference in the size of a land cover class between T2-2014 and T1-2000 with least difference in T35B and most change in S50E. Allocation disagreement occurs where the size of the class remains the same but the spatial distribution changes. Exchange disagreement describes where swapping between two land cover class' pixels have occurred with largest exchange in T12A of almost 11% and is indicative of misallocated classes. Shift refers to the difference remaining after subtracting quantity difference and exchange from the overall difference (Pontius and Santacruz 2014) and generally refers to swapping of more than two land cover classes. Figure 4.5b clearly shows the large contribution loss of grassland plays in S50E and T12A, while woody vegetation has decreased the most in T35B. The gain in urban areas can be seen for S50E and T12A.

Figure 4.6 shows at category level, the areas of change per land cover class (left panel) and for the same class, the intensity of change (right panel) with uniform change intensity of 1.4% indicated. At category level, the left panel of Figure 4.6 shows that UG has the largest size in terms of gains but also the largest losses. This is simply because UG accounts for the largest percentage of the landscape. The corresponding right panel of Figure 4.6 shows the annual intensity of the change activity, which for UG is lower than the uniform intensity. Classes with highest change intensity (both gain and loss) are WI and BRS which based on size, covers only a small part of the catchments. Higher than uniform gain intensity for UrBu is noted in all three catchment, which also translates into large areas of change in S50E and T12A, also seen in Figure 4.6. A balance between loss and gain is indicative of "swap" within the landscape, e.g. removal of class FP in one region, but with expansion of FP within another area within the catchment. Exchange and shift in Figure 4.6 show at interval level that a large proportion of the overall change can be ascribed to two (exchange) or more (shift) classes changing position in the landscape over the study period. Only in T35B is there a large gain in FP area, with associated high intensity. In S50E and T12A, the loss of FP with corresponding high intensity is noted. Woody encroachment is clearly visible in all catchments with change intensity higher than uniform on both losses and gains. T35B is the only catchment that shows a net loss of FITBs (~4%), while in S50E and T12A, there is a net gain in FITBs.

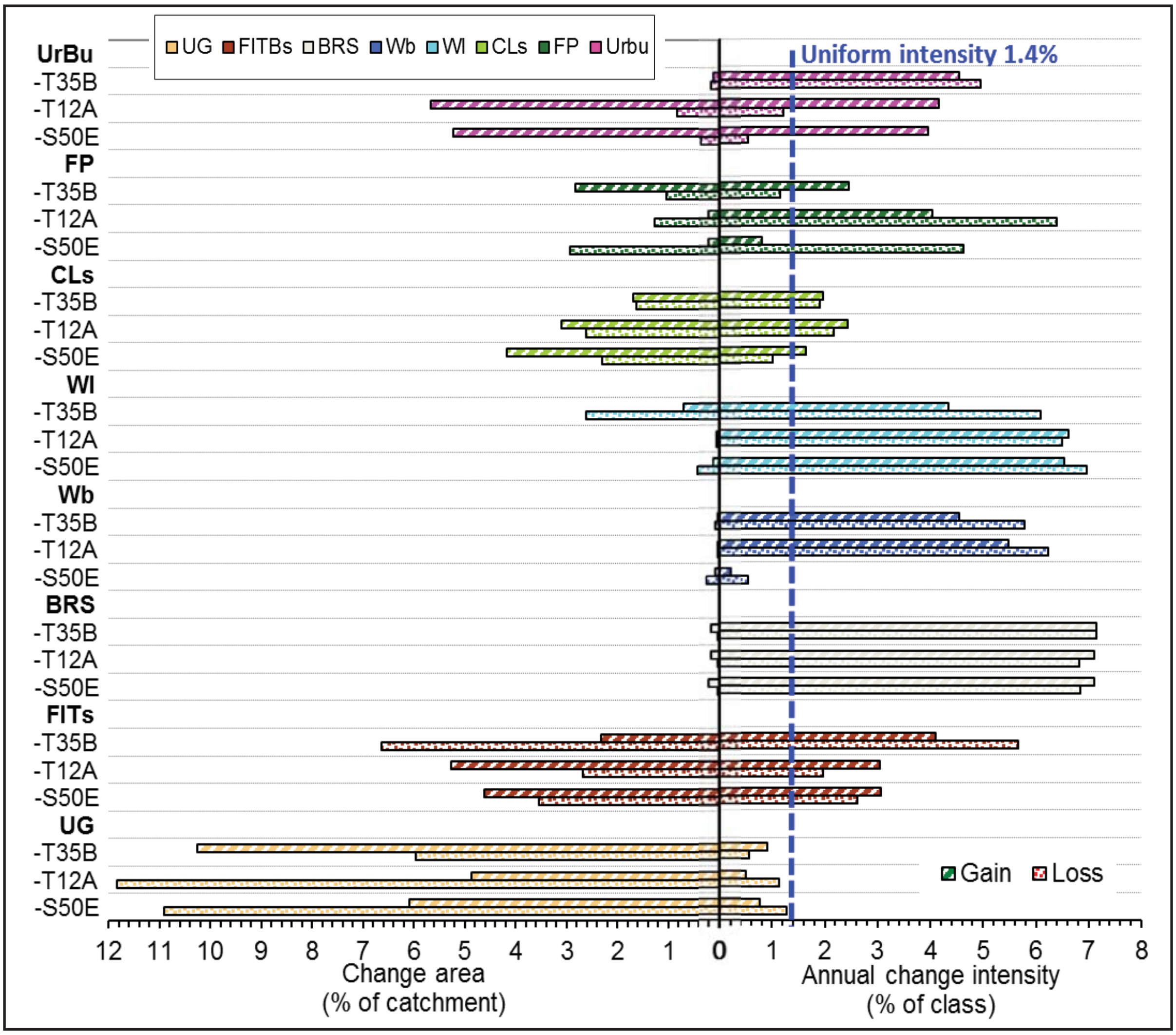

Figure 4.6 Category level change area (left) and intensity (right) expressed as percentage of class

The net gain of FITBs noted for S50E was less than uniform but in T12A, FP was actively targeted. This again may be indicative of classification error in either T1-2000 or T2-2014 where confusion between indigenous forest and plantation may have occurred and may have contributed to the large exchange disagreement in T12A (Figure 4.6). Overall, at transition level, UG is systematically targeted by FITBs, but UG also targets FITBs. The same relationship exists between FP and FITbs and UrBu and CLs. Wl and BRS also show high intensity of loss and gain, especially in T35B, but the extent of the classes is all and contribute to less than 1% of the change in the catchments. However, this may be indicative of error in the input land cover maps.

Indicator-based approach

The land cover class conversions that were allocated to a LCC label representing conversion trajectories as specified in 14 are presented in Table 4.8. The percentage of the catchment assigned to a particular trajectory is noted.

Table 4.8 Land cover change trajectories. Total persistence (labels Pf+Pu+P) are highlighted in grey.

	Dynamic between T1-2000 and T2-2014					
	T35B		T12A		S50E	
	ha	%	ha	%	ha	%
Pf: FITBs persistence	683	2	1 984	7	2 746	6
If: FITBs intensification	916	2	1 466	5	2 066	5
Re: Reclamation	2 394	6	652	2	1 275	3
Pu: Urban persistence	28	0	1 133	4	1 892	4
Iu: Urban intensification	49	0	1 582	6	2 343	5
P: Persistence	31 488	80	19 364	70	30 843	69
Ia: Agricultural intensification	671	2	865	3	1 869	4
R: Afforestation	1 121	3	54	0	91	0
D: Deforestation	356	1	136	1	572	1
De: Degradation	-	-	-	-	-	-
Dn: Natural dynamic	779	2	15	0	187	0
A: Abandonment	533	1	555	2	720	2
E: Exceptionality	530	1	60	0	155	0

Land use patterns in all three catchments are characterised by high persistence, highlighted in grey in Table 4.8, with close to 80% of the total area showing the same land cover in 2014 as in 2000 (82%, 81% and 79% in T35B, T12A and S50E, respectively from Pf+Pu+P from Table 4.8). Both Urban persistence (Pu) and FITBs persistence (PF) are substantial in catchments T12A and S50E (Münch et al. 2017). Urban intensification was highest in T12A (6%) and S50E (5%). Agricultural activities intensified with S50E showing the highest increase in area (4%). Readers are referred to Münch et al. (2018) for details.

Intensification of woody vegetation (If - FITBs have substituted previous land cover), ranged from 2% (T35B) to 5% (T12A), however replacement of woody vegetation by grassland and bare areas (Re – Reclamation) was less than four percent over all three catchments, with highest value of 6% in T35B. Reclamation (Re) in T12A and S50E accounted for less than three per cent. Transitions from plantation, labelled Deforestation (D) covered less than one per cent of the total study area extent. In T35B, transition to plantation, labelled Afforestation (R), accounted for less than three percent of the catchment. Similarly, Degradation (De) linked to conversion from grassland to bare soil characterised less than one per cent of land transformation.

4.7 Projection

This section looks at future scenarios for land cover change in two of the catchments, S50E and T35B and is an abridged version of Gibson et al. (2018).

Changing land use is an anthropogenic dynamic which can have a profound influence on the functioning of landscapes and ecosystems. Seemingly small shifts between agriculture, forestry, urbanisation and even the - at one time - perceived beneficial introduction of alien vegetation may not appear to have much impact at local scale but, when considered across a landscape, the modifications generally lead to more degraded environment. Fragmentation is also more likely in a degraded environment leading to loss of ecosystem function and biodiversity. Land use land cover change (LULCC) with its link to biodiversity loss is being studied to understand the implications for land management, as a change in land cover will have a direct effect on the hydrological functioning of a catchment.

LULCC can be anthropogenic intentional or unintentional with five main drivers in southern Africa: commercial afforestation, woody encroachment, urbanisation, increased dryland cultivation and rangeland degradation. The grassland biome provides ecosystem services of forage production, water supply, habitat, biodiversity, carbon sequestration and recreation. Invasion by alien woody plants in this biome is disrupting the ecosystem service provision. The ecophysiology of individual land covers affects both the water use and the net ecosystem carbon exchange of the landscape. Also the surface reflectance of a landscape is altered with LULCC which results in a change in surface radiation with knock on impacts of surface heating. Thus LULCC impacts not only on local biodiversity and ecosystem function but can have broader implication for catchment water management and climate change.

An understanding of the trajectories in LULCC can identify areas most at-risk of degradation and land management interventions can be targeted to at-risk areas.

4.7.1 Land cover change prediction (2030)

Land cover change from 2000 to 2014 had already been analysed for the study area in this chapter to establish LULCC trends and with a similar time frame in mind, future scenarios for 2030 were explored for catchments S50E and T35B. Already extensively described in this report, in S50E, mixed farming (dualistic farming system) is practiced under communal land tenure arrangements and includes both livestock grazing and crop cultivation (Kakembo 2001). Contrary to this, in T35B, the land tenure is predominantly freehold, and land cover comprises extensive dryland cultivation, commercial afforestation and extensive unimproved grassland for livestock production.as representative of a dual farming system and T35B as representative of commercial farming system. Thus a comparison of future scenarios for two different systems can guide land management of the catchments going forward.

4.7.2 Background and method

Background

Land Change Modeller (LCM) integrated into IDRISI Terrset 18.08 (software created by Clark Labs), provides tools for the assessment and projection of land cover change. LCM was developed by Clark Labs in conjunction with Conservation International to provide a suite of tools to address the problems of accelerated land conversion and the analytical needs required in biodiversity conservation (Eastman 2016). The approach used in LCM is to analyse changes in land cover between two past time steps, in this case where T_1 is 2000 and T_2 is 2014, and use Multi-layer Perceptron (MLP) with explanatory spatial variables to create transition potential maps. Spatial explanatory variables are GIS datasets representing drivers of the observed change (Pérez-Vega et al. 2012) and are typically based on biophysical or socio-economic criteria For example, slope, distance to roads and settlements, land tenure and soil types (Mas et al. 2014) and can be grouped into sub-models if the underlying driver of change is assumed to be the same for each transition (Pérez-Vega et al. 2012). For example, the processes which affect a land cover being changed from forest to urban may be the same as those which affect grassland being converted to urban. This urbanisation transition may be driven by proximity to existing urban areas, proximity to road networks and may have the same topographic driver such as flatter areas are more likely to transition than steep areas. In this example, forest to urban and grassland to urban can be grouped in the same transition or sub-model and the explanatory spatial variables would be the same.

Markov Chain Analysis then assigns the probability of change determined by projecting the historic change to the future, which together with transition potential maps, present a land cover scenario for some future data, T_3, in this case 2030. Concurrently, the individual transition potential maps are aggregated to create a map indicating the propensity of the landscape to experience change.

The output of LCM is thus two predictors: soft prediction and hard prediction. Soft prediction, or potential to transition, is a continuous mapping of vulnerability to change (Eastman 2016). It is calculated by aggregating all the transition potentials and provides an indication of the degree to which the areas have the right conditions to precipitate change. The soft predictor thus provides a likelihood of a cell to experience land cover change without providing an indication as to what the new land cover will be.

The hard prediction procedure used by LCM is based on TerrSet's multi-objective land allocation (MOLA) module and is a scenario of land cover at some future date, T_3, which in the case of this research is 2030.

Method

Land cover maps at 30 m pixel resolution (Okoye 2016), for T_1 (2000) and T_2 (2014) were used to create 1) transition potential maps for each transition, 2) a projected potential for transition map and 3) a predicted land cover map for 2030 (T_3) for S50E and T35B. An identical land cover legend consisting of eight land cover classes was used for each time step (Münch et al. 2017).

Trajectories of land cover change describing both change and persistence were identified and each possible transition of land cover between T_1 and T_2 was labelled and land cover transitions with common underlying drivers of change (Table 4.9) were grouped into sub-models representing (1) intensification - the transition of a lower intensity to a higher intensity usage; (2) afforestation - the planting of commercial trees; (3) deforestation - the clearance of trees; (4) reclamation, degradation and abandonment related to conversion to grassland and bare areas; (5) natural dynamics - seasonal conversions not explained through anthropogenic change; and (6) exceptionality - associated with potential map errors (Münch et al. 2017).

Of particular importance are areas where another land cover class has potentially been replaced by IAPs (FITB intensification) and where forests (indigenous or alien) and other woody areas have disappeared or been removed (reclamation, deforestation). A change from any other land cover class (with the exception of waterbodies and wetlands) were labelled Iu: Urban intensification. It was not possible to determine change in the intensity of agricultural activities due to image resolution, but conversion to agricultural practices was identified (agricultural intensification). Transition sub-models are presented (Table 4.9).

Table 4.9 Transition sub-models and descriptors for catchment S50E and T35B

Transition sub-model	Description	Land cover transitions*+
If: FITBs intensification (↑FITBs)	Woody natural and artificial vegetation substitutes previous land cover	UG to FITBs; **FP to FITBs**; CLs to FITBs
Ia: Agricultural intensification (↑Agric)	Agricultural activities substitute previous land cover	UG to CLs; FITBs to CLs; **Wb to CLs***; Wl to CLs; UrBu to CLs; *FP to CLs*+
Iu: Urban intensification (↑Urban)	Urban activities substitute previous land cover	UG to UrBu; **CLs to UrBu***; FITBs to UrBu
R: Afforestation (↑Forest)	Other land covers are converted to plantations	UG to FP; FITBs to FP; *WL to FP+; CLs to FP+*
D: Deforestation (↓Forest)	Plantations converted to other land covers	FP to UG; **FP to BRS***; *FP to Wl*+
A: Abandonment (Abandon)	Urban and agricultural areas converted to grassland and bare areas	CLs to UG; UrBu to UG; *CLs to Wl*+
Dn: Natural dynamic (Natural)	Areas where natural changes occurred	UG to Wb; UG to Wl; Wb to UG; Wl to UG; *FITBs to Wl*+
De: Degradation (Degrade)	Shrub area converted to grassland and bare areas	UG to BRS
Re: Reclamation (Reclaim)	Woody natural and artificial vegetation areas converted to grassland and bare area	FITBs to UG

***Bold text** shows transitions which occurred in S50E only; +*italics* show transitions that occurred only in T35B.

In choosing explanatory variables, the processes producing land cover change need to be visualised after which a spatial dataset of the particular process must be sourced at appropriate spatial resolution. GIS data sets were identified to describe the potential transitions; geoprocessing was performed to represent the particular process. The spatial datasets selected included slope, aspect, distance from rivers, distance from roads, distance from residential areas, distance form forestry, and distance from FITBs.

4.7.3 Results

The results of LCM were presented in maps in Gibson et al. (2018). The probability of a land cover persisting (the diagonal highlighted by *) and of each class transitioning to every other class from the Markov matrix are presented in Table 4.10.

Table 4.11 shows the modelled land cover change based on the proportion of the study area. The loss and gain per class is also recorded with the net loss per land cover class indicated. In S50E, the probability of UG persisting is approximately 80% with the highest probability of UG being lost are to FITBs (~4.5%), CLs (~6.6%) and UrBu (~8.3%), thus FITBs intensification (If), agricultural intensification (Ia) and urban intensification (Iu) are at the expense of grasslands, constituting ~12% of the catchment (5,283 ha) as shown in Table 4.17. The probability of 34% FITBs loss to UG (Table 4.16), possibly due to alien invasive clearing programs, may seem high, but in reality the number of pixels that can in fact transition are limited and the change represents only 4% (1800 ha) of the total area (44,640 ha) in 2030 (Table 4.11). The probability of persistence of FP is low (24%) with a likelihood of transition to FITBs (42%) and UG (34%), which clearly reflects the changes from 2000-2014. Classes WI and BRS also show a very low probability of persisting. In T35B, the probability of UG persisting is over 90% with the highest probability of UG being lost are to FITBs (~3.3%) and FP (3.2%) (Table 4.10).

Table 4.10 Markov matrix probability of land covers in S50E (bold) and T35B (italics) transitioning or persisting (*) from 2014 to 2030. Note land cover abbreviations are given in Table 4.11.

	UG	FITBs	BRS	Wb	Wl	CLs	FP	UrBu
UG	**0.80***	**0.05**	**0.00**	**0.00**	**0.00**	**0.07**	**0.00**	**0.08**
	*0.91**	*0.03*	*0.00*	*0.00*	*0.01*	*0.02*	*0.03*	*0.00*
FITBs	**0.34**	**0.58***	**0.00**	**0.00**	**0.00**	**0.02**	**0.02**	**0.04**
	0.82	*0.10**	*0.00*	*0.00*	*0.01*	*0.03*	*0.03*	*0.00*
BRS	**0.43**	**0.05**	**0.00***	**0**	**0.00**	**0.02**	**0.01**	**0.49**
	0.25	*0.00*	*0.00**	*0*	*0.01*	*0.11*	*0.62*	*0.00*
Wb	**0.03**	**0.00**	**0**	**0.93***	**0**	**0.04**	**0**	**0.00**
	0.56	*0.01*	*0.00*	*0.07**	*0.16*	*0.13*	*0.06*	*0.00*
Wl	**0.52**	**0.01**	**0.00**	**0.00**	**0.00***	**0.43**	**0**	**0.03**
	0.68	*0.01*	*0.00*	*0.00*	*0.06**	*0.12*	*0.13*	*0.00*
CLs	**0.11**	**0.03**	**0.00**	**0.00**	**0.00**	**0.84***	**0.00**	**0.03**
	0.24	*0.01*	*0.00*	*0.00*	*0.03*	*0.69**	*0.02*	*0.00*
FP	**0.34**	**0.42**	**0.00**	**0**	**0.00**	**0**	**0.24***	**0.00**
	0.16	*0.00*	*0.00*	*0*	*0.02*	*0.01*	*0.82**	*0.00*
UrBu	**0.03**	**0.00**	**0.00**	**0**	**0**	**0.05**	**0.02**	**0.92***
	0.46	*0.04*	*0.00*	*0.00*	*0.02*	*0.27*	*0.02*	*0.19**

Table 4.11 Modelled land cover change as a percentage of the study area for S50E (bold) and T35B (italics), * denotes persistence

Change	UG	FITBs	BRS	Wb	Wl	CLs	FP	UrBu	Total 2014	Loss	Net
UG	**44.7*** *72.7**	**3.2** *2.7*	**0.1** *0.1*	**0.1** *0*	**0.1** *0.5*	**4** *1.3*	**0.1** *2.6*	**4.7** *0.1*	**56.9** *79.9*	**12** *7.2*	**-4.8** *-0.2*
FITBs	**4** *3.3*	**5.5*** *0.4**	**0** *0*	**0** *0*	**0** *0*	**0.3** *0.1*	**0.2** *0.1*	**0.5** *0*	**10.5** *4*	**5.1** *3.6*	**-0.6** *-0.9*
BRS	**0** *0*	**0** *0*	**0.1*** *0.2**	**0** *0*	**0** *0*	**0** *0*	**0** *0*	**0** *0*	**0.1** *0.2*	**0.1** *0*	**0.1** *0.1*
Wb	**0.1** *0*	**0** *0*	**0** *0*	**2.6*** *0**	**0** *0*	**0.1** *0*	**0** *0*	**0** *0*	**2.9** *0*	**0.3** *0*	**-0.2** *0*
Wl	**0** *0.8*	**0** *0*	**0** *0*	**0** *0*	**0*** *0.1**	**0** *0.1*	**0** *0.2*	**0** *0*	**0.1** *1.2*	**0.1** *1.1*	**-0.01** *-0.3*
CLs	**2.2** *1.5*	**0.5** *0.1*	**0** *0*	**0** *0*	**0** *0.2*	**15*** *4.3**	**0** *0.2*	**0.7** *0*	**18.2** *6.2*	**3.4** *1.9*	**1.7** *-0.2*
FP	**0.6** *1.3*	**0.7** *0*	**0** *0*	**0** *0*	**0** *0.1*	**0** *0*	**0.4*** *6.8**	**0** *0*	**1.8** *8.3*	**1.4** *1.5*	**-1.1** *1.5*
UrBu	**0.3** *0.1*	**0.1** *0*	**0** *0*	**0** *0*	**0** *0*	**0.6** *0.1*	**0** *0*	**8.5*** *0.1**	**9.5** *0.2*	**1** *0.1*	**4.9** *0*
Total 2030	**52.1** *79.7*	**9.9** *3.1*	**0.2** *0.3*	**2.7** *0*	**0.1** *0.9*	**20** *6*	**0.7** *9.8*	**14.4** *0.2*	**100** ***100***	**23** ***16***	
Gain	**7.4** *7*	**4.4** *2.7*	**0.1** *0.1*	**0.1** *0*	**0.1** *0.8*	**5.1** *1.7*	**0.3** *3*	**5.9** *0.1*	**23** *16*		
Change per year									**1.5** *1*		

Based on the cross tabulation of land cover classes (Table 4.11), it was determined that the total change (gain and loss) in the landscape for catchment S50E over all land cover classes was 23% for predicted period 2014 to 2030, compared with 21% for the period between 2000 and 2014 (Münch et al. 2017), assuming a similar map accuracy for the modelled map. Since the future scenario model mimics patterns of past measured change, the change intensity, defined as the change per year, remained constant at 1.5% per year for S50E. UG, the largest class, also has the largest loss, though this relatively large dormant class, shows a higher change intensity during the modelled period with the loss intensity increasing from 1.27% to 1.34%. In contrast to the measured change, a net loss was modelled for FITBs. However, the predicted loss falls within the 30% hypothetical error in landscape transition ascribed to error propagation from contributing land cover maps calculated by Münch et al. (2017). Net change in FITBs for 2000 to 2014 varied between -0.5% to +1% of total catchment area. In T35B, the total change (gain and loss) in the landscape over all land cover classes was only 15.5% for prediction period 2014 to 2030, compared with 18.2% for the period between 2000 and 2014 (Münch et al. 2017). The change intensity decreased from 1.3% to less than 1% for T35B. FP showed a small net gain. Intensification of FITBs were modelled in the upper reaches of the Pot River and Little Pot. While FITBs systematically targets UG in transition (If), clearing of FITBs also systematically results in UG (Re), though possibly degraded, with a net loss of FITBs over the period. Afforestation (increased FP) is the strongest trajectory in T35B showing a net gain of 1.5% with FP targeting WI. This transition may be the result of the low accuracy of the WI class in the 2014 input land cover dataset.

4.7.4 Implication of projections on land management

Land cover change, which is closely linked to rural development initiatives, presents challenges for integrated land and WRM in the Eastern Cape. The aim of this research was to project land cover change trends into the future (2030) to gain an understanding of the implications on biophysical parameters which in turn can guide land management strategies. However, the complex processes of land cover change are difficult to capture in variables, and model in algorithms, since they are often shaped by dynamic, non-linear human-nature interactions (Camacho Olmedo et al. 2015). Gibson et al. (2018) discuss model assumptions which may impact on the scenario predicted by the LCM. Nevertheless, in the context of trying to understand appropriate land management interventions for both catchments in light of the trends presented in the results, a qualitative discussion of biophysical parameters that impact on catchment water use, NEE and the surface energy balance and the expected land cover transitions is given.

Firstly, from a WRM perspective, globally, >66% of the total precipitation over land is returned to the atmosphere as ET which makes ET very important in catchment water balance. During photosynthesis, plants accumulate new biomass as they release water in exchange for atmospheric carbon and ET rates are closely related to the carbon assimilation rates of plants (Franks et al. 2013). It is well-established that knowledge of land cover can give insight (via ecosystem surface conductance and ET) into the water use of the land surface. A transition towards land covers with higher surface conductance will result in higher water use via ET in the catchment. In this study the loss of grasslands favouring an increase in anthropogenic land covers (agricultural and FITBs intensification) will result in higher catchment ET for both S50E and T35B with T35B being most impacted.

Next, from a carbon perspective, fPAR and LAI measured by Palmer et al. (2017) and used in NEE and ET modelling respectively, indicate that both fPAR and LAI are lower for unimproved grasslands than for potential transition classes (Intensification of FITBs and Intensification of CLs and afforestation). These transitions will thus represent a gain in both catchments NEE and ET, and a concomitant decrease in runoff. From a carbon storage perspective, the transitions will result in more carbon storage, which from a climate change outlook may be seen as a positive change, however in an already water scarce catchment, further water demands by the vegetation will result in a decrease in the availability of water for other land covers.

Finally, when considering the surface energy balance, the changes to surface albedo that will accompany these land cover trajectories are less certain. Given that there is a general increase in woody green biomass as a result of both afforestation and continued invasion by IAPs, the findings of Rotenberg and Yakir (2010) make it likely that the decrease in surface albedo from these cover classes will result in an increase in the absorption of energy, with a resultant rise in temperature. This decrease in albedo may however be counteracted by an increase in degraded surfaces associated with rural housing and in the unimproved grasslands where continuous grazing by livestock changes species composition and cover. Rangeland degradation is commonly associated with the changes in land tenure that are occurring in this catchment (Bennett et al. 2012), and a reduction in the basal cover of herbaceous plants (mainly grasses) is the first noticeable change. This results in a surface with higher albedo.

Since, the land surface reflectance (albedo) affects net surface radiation, dark vegetation with a high LAI will have a lower albedo than open grasslands and it can be postulated (however this must still be measured) that the transitions modelled in the S50E catchment could lead to an overall lowering of albedo in the catchment. An increase in net radiation is thought by some to be a driver of global warming, however, Bonan (2008) states that surface warming arising from the low albedo of forests is offset by strong evaporative cooling. Thus the impact of a change in albedo in this catchment remains speculative but is a research avenue which should be pursued.

4.8 Conclusions

4.8.1 Measurement and modelling of ET

Based on the model evaluation metrics, the PML performed better than the PMP model and hence, the calibrated values may be applied across grasslands in South Africa with reasonable confidence. The good performance by the f_{zhang} approach was encouraging since the PML can now be applied using data that is readily available, with only g_{sx} as a model parameter to be determined. The good performance of the PML in Truro farm where validation was conducted using parameters calibrated at Somerton farm suggest that sparsely distributed weather stations can confidently be used to derive reasonable ET over wide areas. The inadequacy of the PMP model to simulate observed ET in the study area confirmed the importance of E_s in such environments and, therefore, the PMP model could be improved by adding an E_s component.

The study developed credible algorithms for estimating ET in semi-arid areas by advancing the preliminary work of Palmer et al. (2014). The addition of the E_s component resulted in good agreement between the observed and modelled ET. The simple two-layer model described in this study will make it possible to estimate ET in data scarce areas by using widely available meteorological data, MODIS LAI and surface albedo without the need for reverse engineering. This is particularly crucial in regions where there are no networks of flux tower stations for validation purposes. However, the model had limitations in reproducing stomatal behaviour over specific vegetation species. In semi-arid areas, accounting for E_s is crucial since it contributes a significant proportion to total ET. Consequently, attempts to develop algorithms based on VIs were not successful since these cannot estimate E_s. The LAI and ET0 were useful predictors of ET across the sites and this enabled the development of algorithms for predicting ET on a biome scale and this is vital for data scarce areas.

The evaporative index proved to be useful in tracing the effects of land cover change on AET. Therefore, the observed dynamics in AET could largely be linked to land cover changes as shown by dynamics in the *w* and land cover maps. However, dramatic land cover change in some cases does not result in a corresponding change in AET as observed in the grassland cover type. In such cases, global processes related to warming/ increasing droughts also seem to indirectly modulate evapotranspiration. There could be a strong connection between sub-surface and surface water in driving AET since the evaporative index was >1 in some cases. Runoff could also have provided excess water for riparian vegetation. The *w* suggests that the catchment hydrological response is sensitive to land cover changes and hence looking to the future, management interventions are required to enhance water retention in the catchment. There are still uncertainties in the MOD16 ET product in the study area and the need for model refinement and long-term validation datasets is important to fully evaluate the model. Dramatic land cover influenced AET and this could undermine the ability of grassland to deliver ecosystem services related to ranching operations.

4.8.2 Influence of Acacia on grass production

The results revealed that *A. mearnsii* has changed the landscape by impacting on nutrients that influence growth properties of vegetation, soil physical attributes such as bulk density coupled with micronutrients availability as well as acidification of the soil which in turn partly influenced the availability of inorganic P. Therefore, the management of invaded landscapes in this CSES should aim to maximize the soil fertility benefits defined by the observed principal components from the present study. The study has also developed regression equations to predict above-ground grass biomass using non-destructive methods (line transect and DPM) and there was agreement between these two independent methods as well as other published studies, which validates the results. Recovery thresholds have not been surpassed in the study area given that background above-ground grass biomass production can still be attained if clearing is not accompanied by active soil management interventions.

Acacia mearnsii is far from being eradicated since it is still spreading as evidenced by many small stemmed trees across the sampling sites The high biomass reported in this work can provide business opportunities through selling the *A. mearnsii* stands to the forestry industry and in the form of carbon credits under the auspices of REALU. Grass production can still be viable in areas infested by *A. mearnsii*. Canopy cover of *A. mearnsii* was the most critical variable, since beyond specific LAI thresholds, grass production was impeded. In socioecological settings such as reported in this study, reducing *A. mearnsii* canopy LAI through thinning could be critical to enhance multi-benefits of the invaded landscape such as grazing and carbon sequestration. The relationships between NDVI and LAI developed in this paper can be used to target areas for thinning. This may be crucial in improving livestock production in such socio-ecological landscapes. Although thinning could invariably mitigate allelopathic effects, more intensive experimental work still needs to be conducted to understand the response of South African grasslands to canopy thinning. This will enable communities to get more value out of the invaded landscapes.

The results presented in this chapter are an abridged version of information presented in the following papers:

GWATE, O., MANTEL, S. K., FINCA, A., GIBSON, L. A., MÜNCH, Z. and PALMER, A. R. (2016) 'Exploring the invasion of rangelands by *Acacia mearnsii* (black wattle): biophysical characteristics and management implications', *African Journal of Range & Forage Science*, 33(4), pp. 265–273. doi: 10.2989/10220119.2016.1271013.

GWATE, O. (2018) The effects of *Acacia mearnsii* (black wattle) on soil chemistry and grass biomass production in a South African semi-arid rangeland: implications for rangeland rehabilitation. In GWATE, O. (2018) *Modelling plant water use of the grassland and thicket biomes in the Eastern Cape, South Africa: towards an improved understanding of the impact of invasive alien plants on soil chemistry, biomass production and evapotranspiration*. PhD thesis. Rhodes University, Grahamstown,pp. 27 – 55.

GWATE, O., MANTEL, S. K., PALMER, A. R., GIBSON, L. A. and MÜNCH, Z. (2018a) 'Measuring and modelling evapotranspiration in a South African grassland : Comparison of two improved Penman-Monteith formulations', *Water SA*, 44(3), pp. 482–494. doi: 10.4314/wsa.v44i3.16

GWATE, O., MANTEL, S. K., GIBSON, L. A., MÜNCH, Z. and PALMER, A. R. (2018c) 'Exploring dynamics of evapotranspiration trends in selected land cover classes in a sub-humid region of South Africa', *Journal of Arid Environments*, 157, pp. 66–76, doi: 10.1016/j.jaridenv.2018.05.011.

GWATE, O., MANTEL, S. K., FINCA, A., GIBSON, L. A., MÜNCH, Z. and PALMER, A. R. (2018d) 'Estimating evapotranspiration in semi-arid rangelands: connecting reference to actual evapotranspiration and the role of soil evaporation', *African Journal of Range & Forage Science*, doi:10.2989/10220119.2018.1505779.

GIBSON, L., MÜNCH, Z., PALMER, A. and MANTEL, S. K. (2018) 'Future land cover change scenarios in South African grasslands – implications of altered biophysical drivers on land management', *Heliyon*, 4(7). doi: 10.1016/j.heliyon.2018.e00693.

CHAPTER 5 POSSIBILITY OF USING A RES SYSTEM IN RURAL RANGELANDS AS CONTRIBUTION TOWARDS THE RESOLUTION OF DEGRADATION AND WATER ISSUES

by

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5.1 Introduction

This chapter provides a summary of the social engagement conducted by various project team members and consultants via field surveys and the project's yearly workshops. Section 5.2 reports on a study whose aim was to investigate what local people in two villages of Mgwalana and Mahlungulu in northern Eastern Cape, South Africa understand about ecosystem services. It considers the implications of these findings on planning of intervention programs. The ecosystem service (ES) concept emphasises the importance of the role that nature plays in human well-being. It provides both a new framework for looking at nature, and a tool for guiding planning of intervention programmes for ecological management and rehabilitation that include various forms of PES.

Section 5.3 and 5.4 present the findings from workshops in project year 1 to 3 related to grasslands and clearing of wattle. The first workshop's aim was to determine what, where, and how land use practices are determined in order to conceive of future intervention strategies. Workshops in year 2 and 3 followed on highlighting business opportunities and access to markets for the communities.

5.2 Ecosystem services conceptual framing

An ecosystem is defined as "a dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit" (United Nations Convention on Biological Diversity; https://www.cbd.int/convention/articles/default.shtml?a=cbd-02). These interactions in some instances produce ecosystem services. These services are defined in several ways (Daily 1997). "Ecosystem services are the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life. They maintain biodiversity and the production of ecosystem goods, such as forage, timber, biomass fuels, natural fibre, pharmaceuticals, industrial products, and their precursors" (Daily 1997: pg. 3). Additionally, Costanza et al. (1997) define ecosystem services as "the benefits human populations derive, directly or indirectly, from ecosystem functions". In some instances, commentators, especially those with an environmental economics leaning, distinguish between ecosystem goods and ecosystem services. They refer to the former as tangible and the latter as intangible benefits human beings get from ecosystems (Costanza et al. 1997). In this work we use the term 'ecosystem service' (as an abbreviation for ecosystem goods and services) to refer to both tangible and intangible benefits human beings obtain from ecosystems.

Ecosystem services are classified into four categories: provisioning, regulatory, supporting and cultural services (Millennium Ecosystem Assessment 2005). Provisioning ecosystem services are those that produce goods directly consumed by humans and they include food, fuel, fresh water, fibre, genetic tissues, biochemical natural medicine, pharmaceuticals (generated from raw materials derived from plants) and ornamental resources. Regulatory ecosystem services regulate environmental conditions and provide benefits such as climate control, including soil fertility (land cover, soil organisms, phytoplankton) and pollination (Mertz et al. 2007), reduction of soil erosion (Leuning et al. 2005; Dale and Polasky 2007), air quality maintenance, water regulation, water purification, human disease control, water damage mitigation, protection of wetlands and beach forests (Proctor et al. 2008), climate stabilisation and coastal protection (Millennium Ecosystem Assessment (MA) 2005). Cultural services are non-material benefits that are closely linked to human systems of value, behaviour, political, social and economic organisations. They include recreation and tourism, cultural heritage values, sense of place, social relations, aesthetic values, educational values, as well as spiritual and cultural values. Overall, these benefits lead to spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences (Frumkin 2002; Millennium Ecosystem Assessment 2005).

Supporting ecosystem services are those services that are necessary for the provision of all other ecosystem services, including provisioning, regulatory and cultural services. Whereas the impact of all the other three categories on people are more immediate and direct, supporting ecosystem services impact on people more indirectly, and their effects tend to take a very long time to be felt. Soil formation is an example of supporting services. While the formation of soil does not directly impact on the lives of human beings, it indirectly affects them through its influence on food production. Other examples include primary production (production of their own food by plants), production of atmospheric oxygen, soil formation and retention, nutrient cycling, water cycling, and provisioning of habitat.

Two-thirds of ES are in decline worldwide (Millennium Ecosystem Assessment 2005). Human demands for ecosystem services may exceed the Earth's ability to provide (Watson et al.

1998) because land use and resource extraction strongly affect how those ES are provided by natural resources and managed landscapes (Lambin et al. 2003). ES are clearly necessary (Chan et al. 2006) and important to those who depend upon the land for their survival (Oleson et al. 2018), including non-humans.

A common and dominant feature in the debates about ES and definitions of ES is that they tend to betray an anthropocentric worldview of ecology; they emphasise the centrality of human beings and human interests in ecosystems. Accordingly, mechanisms to re-shape and influence human behaviour and attitude towards nature are being formed and propagated. One such mechanism is the RES concept (Milder et al. 2010) or what has also been termed Compensation and Rewards for Environmental Services (CRES). Swallow et al. (2009) defined CRES as “contractual arrangements and negotiated agreements among ecosystem stewards, environmental service beneficiaries, or intermediaries, for the purpose of enhancing, maintaining, reallocating or offsetting damage to environmental services.”

Whose ecosystem services?

The question ‘What are ecosystems and ecosystem services?’ has attracted considerable interest especially in the past decade (Boyd and Banzhaf 2006; Wallace 2006; Fisher and Turner 2008; The Economics of Ecosystems & Biodiversity [TEEB] 2010). TEEB (2008) argues that it is important that people and communities recognise the value of ecosystems because knowing their value will ensure that they practice proper management and sustainable use of natural resources. To sustain the continued flow of ecosystem services “requires a good understanding of how ecosystems function and provide services, and how they are likely to be affected by various pressures” (TEEB 2010: 6). In order to build this necessary threshold of understanding, TEEB (2010) implores us to tap into the insights of the natural sciences and to appreciate the economics of natural resources. Further emphasising the centrality of economic thinking in ecosystem management, TEEB (2010: 8) posits that “the failure to account for the full economic values of ecosystems and biodiversity has been a significant factor in their continuing loss and degradation”.

Rodríguez et al. (2006) note that although ES have been acknowledged by the research community as an important societal value, researchers pay little attention to the social aspect of the subject. “Most ecosystem valuation research is too focused on the question of what is the value and not enough on what, in particular, people value” (Rodríguez et al. 2006). Apart from knowing what people value, we add that researchers should strive to understand what the people know of ES as a building block to construct and place monetary values on these services. Achieving this requires the use of robust in-depth study techniques that are capable of revealing nuances of local knowledge and value systems in so far as they concern and depict human-nature relations. The purpose of doing this is to both help us understand the values of ES with others (the laymen and laywomen) and that valuation methods and value tags that are rooted in local ecological value and experientially constructed knowledge systems, are likely to be more locally comprehensible than systems that are less localised and more abstract, using the grand-axioms and laws of welfare economics.

The idea is not to propose an alternative to the use of scientific ways of knowing, but rather, to complement science, and to help improve its ability to capture and address world problems by leveraging the strengths of other ways of knowing. This epistemic approach is underpinned by the belief that knowledge systems(s) are plural rather than singular, and that such knowledge systems work more effectively in relationships of mutual complementarity than they do in substitutional or alternativist mode of relations, in which one system is privileged as the silver bullet.

In this work, we used lay knowledge systems to unravel locally based meanings of, and perceptions about, ES and their varied values. But one major critique of a lay knowledge system is that it is context specific, for it largely depends on specific events at a certain time period, and in a particular set of spatial circumstances. Some commentators have reduced lay knowledge to being "anecdotal and idiosyncratic" and therefore argue that it cannot constitute a general tool for understanding the world (Babbie and Mouton 2001). However, what this critique misses is that, because it is based on personal experience and observation, lay knowledge may be closer to the ground and can be relevant in a particular context. Thus, the fact that it is context specific renders it a suitable tool to address local and context specific problems. After all, it is very "rich in meaning and symbolism" (Babbie and Mouton 2001).

Re-engaging the reward for ecosystem service concept

The concept of rewards for ecosystem services (RES) is gaining increasing attention as a means of translating external, non-market values of ecosystem services into tangible incentives for local actors to benefit financially. As a policy instrument, RES is described as particularly suited to addressing environmental problems in ecosystems that are mismanaged because associated benefits are externalities from the perspective of ecosystem managers.

Recent research work conducted in communal lands in southern Africa has focused on both propagating this concept and finding appropriate RES models in which different ecosystem services can be assigned monetary values to incentivise communities to adopt good management practices of their natural resources. Favretto et al. (2016) used a MCDA to determine the monetary and non-monetary values of ecosystem services in the rangelands of Botswana's Kgalagadi District. More recently, Favretto et al. (2017) used stochastic simulation "to estimate the range of potential monetary outcomes of rangeland ecosystem services under different land uses, including consideration of the uncertainty and variability of model parameters" in the same area.

While it is well-appreciated that the RES research efforts are producing novel information and are moving the ecosystems research agenda in the right direction, we argue that - unless the twin concepts of ecosystems and ecosystem services are well understood by the people together with whom such research enquiries are carried out - research enquiries on RES are very difficult to conduct or results thereof to get to be effectively analysed, and to speak to the actual on-the-ground realities.

The term 'ecosystem service' is relatively new. Like the term 'ecosystem' itself, 'ecosystem services' started to be used in the late 1960s in the works of King (1966) and Helliwell (1969). Although African communities have a commendable track record of using indigenous knowledge systems to manage and live in harmony with nature, the discipline of ecosystem management as it is understood and gets articulated today in the corridors of learning and spaces of professional practice, is not familiar to or understood by indigenous communities, especially non-literate rural people, in communal lands. Communal land is not privately owned, as commercial land is, but is held at a community level, usually in terms of some form of official customary (i.e. communally and 'traditionally' oriented) land tenure system. Land may be distributed under the allocatory authority of a leadership structure, whether of a more 'traditional'(i.e. chief/headman) type, or more recently, of a type consisting of a complex combination of 'traditional' and elective political elements.

Meaningful research efforts on building of locally understood and lived notions of values of ecosystem services must be preceded by a thorough enquiry exercise into *de facto* local understandings and experiential encounters of the people's processes of dealing with nature. However, this cannot be achieved by a research design that seeks to tick boxes that are only concerned to find out what the researched know. Rather emphasis must be put on efforts to understand *how the researched know,* embracing participant-perspective -oriented research approaches similar to how social scientists conduct their research.

5.2.1 RES survey

5.2.1.1 Study sites and methods

Two communities situated in the Sakhisizwe Local Municipality in northern Eastern Cape Province were selected, based on their dependence upon ecosystem services to support their livelihoods. These communities are situated in two quaternary river catchments (S50E for Mahlungulu village and T12A for Mgwalana village). Both villages hold their land resources under the customary tenure system and practice mixed farming in the form of livestock and crop production. Both catchments have been invaded by several IAPs, with these invasions dominated by black wattle (*Acacia mearnsii*) and silver wattle (*A. dealbata*).

During this study, we undertook a mixed methods approach (Creswell 2013). In order to give a voice to all social groups in the communities, we included village leaders, local professionals such as teachers, nurses and development workers, but the majority of respondents were ordinary village residents. The survey data were collected using a structured questionnaire designed and loaded onto an Android-enabled handheld-device using Kobo-Collect (www.kobotoolbox.org) for ease of capture, analysis and storage.

Across the two sites, 33 questionnaires were initially administered to develop an understanding of the individual's view of the ecosystem components from which they receive services. This was necessary given that the concept of ES is fairly new and is largely couched in technical scientific terms that are abstract concepts to lay people. This included theoretical learning (Rodríguez et al. 2006), to give insights to, and guide interviewees in their processes of choosing responses. Initial questions on demography (age, gender, dwelling type, profession, employment status, etc.) provided a background on each respondent. A short (200 word) description of each of the four categories of ecosystem service (provisioning, regulatory, supporting and cultural) was recited in Xhosa prior to the respondent's ranking of the list of services they use in order of their importance. Respondents were asked to add any services that were not mentioned in the list.

The closed question technique helped us in our process of ranking ES services according to the values they were given by different respondents. It was anticipated that giving such closed sets of choices would help respondents in ranking option-responses in order of their importance, without losing track of what had to be ranked. In doing this, dedicated effort was made to explain to the respondents what the technical terms meant (with Xhosa translations), and to find out if the same terms were known to the respondent but perhaps in a different couching of language, or a different approach of interpretation.

One major challenge that we found using the structured question technique (that were geared towards quantitative replies) is that interviewees, especially the non-literate and elderly, found it difficult to follow and understand the logic of the multiple-choice technique. When we chose the technique, we had anticipated that it would be helpful in that it would make respondents aware of the possible competing answers, and then pick the best from the list.

Following the initial structured question survey, we focused on questions with less technical terms using an open-ended interview approach where the interviewees could speak in the local language on a topic, and the responses were tape-recorded. An effort was made to ensure that the interview process was as close as possible to a dialogue between the researcher and the researched. The researcher used an interview guide to ask questions, explaining what was meant by the question, and sometimes went as far as giving examples of similar cases that they knew of from elsewhere around the world. The idea was both to share knowledge and to challenge the researched to talk about what they knew about the issue in discussion. It was not necessary that the researcher and researched agree on what should be known about a certain aspect of ES. What was important rather was that the researcher had to empathically understand what, and how the researched knew, about the ES in question. This approach presents a very good opportunity for the research community to forge valuable relations of mutual complementarity between scientific and lay knowledge.

5.2.1.2 Results and Discussion

What do others know? Experiential encounters at Mahlungulu and Mgwalana villages

The research unearthed both common and unusual narratives, but all are equally valued for the purpose of this work. The interviewees talked extensively about how the local communities interact with the natural environment and its features. Over the years of living in the area and through oral tradition and multiple and repetitive encounters with nature, the locals have built a multitude of repertoires of ecological knowledge for both using and managing natural resources.

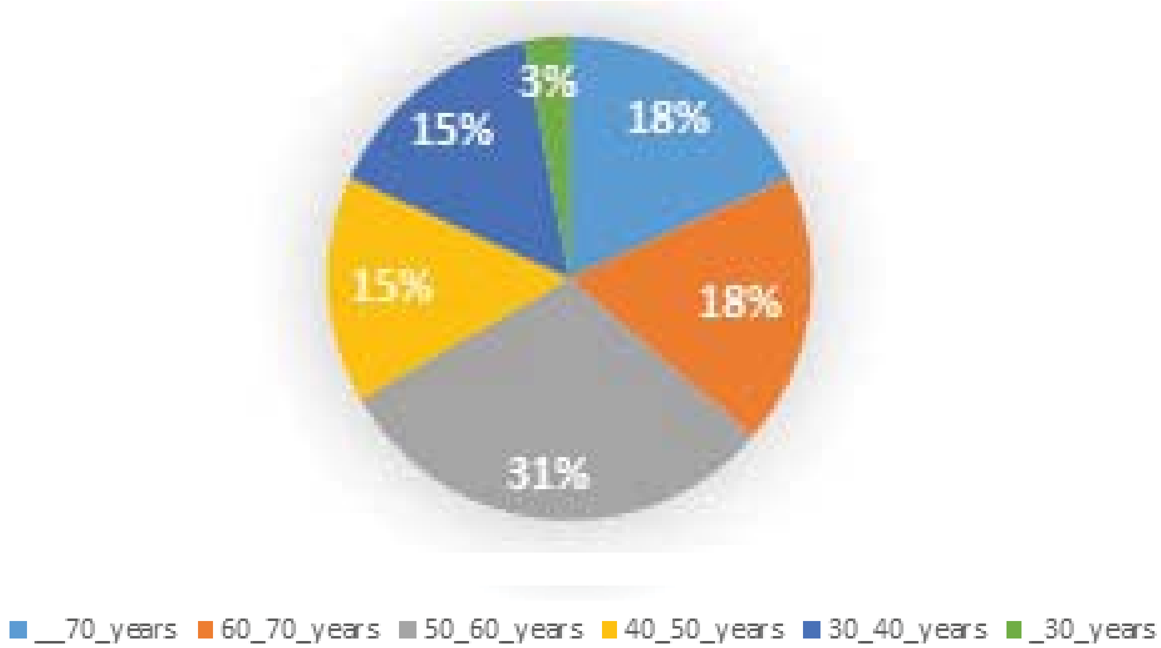

Figure 5.1 Pie diagram of the % of age classes that were interviewed

Figure 5.1 shows the age classes of the 33 respondents in our survey and Table 5.1 shows their primary and secondary occupations (as identified by the respondents) that cover a wide range. We opened our discussion by asking what people's ideas were around the concept of ecosystems. This was a structured question with a set of choices to guide respondents. The concept of the natural environment was easily understood by the respondents and they defined it by mentioning elements (examples of natural resources) that constitute the environment such as grass, rain, wind, soil, trees, animals, birds, rivers, forests etc. In addition, multiple examples of how some of these elements interact together to produce effects on both nature itself and the lives of people were given. One of the most cited examples was about the interaction of rain, soil and plants. Interviewees said when rain meets the soil, plants and vegetation grow. The growing of plants benefits people directly because it leads to increased supply of agricultural foods. Also, growing of vegetation, especially grass, benefits people indirectly because it makes pasture available to domestic animals, such as cattle and goats, which in turn are used as food or income generators by people.

Table 5.1 Types of primary and secondary occupations of respondents

Primary occupation	Number of respondents
Councillor	2
Farmer and herder	2
Traditional healer	3
Farmer and traditional herder	1
Entrepreneur	2
Farmer and home maker	2
Home maker	9
Herder	5
Professional nurse or teacher	5
Professional farmer	1
Traditional leader and Farmer	1

Secondary occupation	Number of respondents
Local water operator	1
Farmer	1
Gardner	1
Health care assistant	1
Committee members	5
Sassa (old age)	3
Labourer at the wattle project	3
Domestic worker	2
Handy man	2
Seller (goods-chicken, vegetables, beads and services- tailor)	4
Shop owner	1
Retired teacher	2
Municipality grader operator	1
Community member	2
Self employed	1
Board member	1
Teacher	1
Herder	1

Provisioning services

Provisioning services were ranked in order of their importance by the respondents (Table 5.2). Water (first choice, 100% response) and grazing pasture were the most known and needed provisioning ES largely because people of Mgwalana and Mahlungulu have historically been basing their livelihoods around livestock ranching (cattle, sheep and goats) and crop cultivation (maize, beans and pumpkins). Although crop cultivation is less vibrant than in the past, the elderly talked fondly of the agricultural past during which arable lands were all green and households were food secure. Herds of cattle and flocks of sheep are said to have declined significantly from what they were in the past. Adverse changes in farming and livestock ranching started at the climax of apartheid governance in the 1970s because of the administration's tactics of social engineering and territorial manipulation which among others saw the forceful implementation of betterment planning (McAllister 1989), forced removals, concentrated settlements and mass labour emigration by rural men to distant mining centres. To this day, people still aspire for a revival of the agricultural past so that households can again eat green mealies, pumpkins and fresh beans from their gardens and drink milk from their kraals.

The following additional services were recognised by respondents:

- Wattle for making cattle kraals and rocks for making foundations for houses
- Soil is used to plough and fruit trees grow without being planted
- Rocks for making kraals
- Fencing from wattle
- Water drawn from the mountains
- Manure from cattle waste
- Mud to paint the inside and outside of traditional houses
- Animal waste to clean the inside of traditional houses

Table 5.2 Provisioning ES according to their importance

Provisioning ecosystem service	Order of importance
Drinking water	1
Pasture for livestock	2
Wood fuel	3
Wood for Building	4
Medicinal plants	5
Veld/Wild foods	6

Cultural services

Cultural ES were second after provisioning in terms of being known to the people. Although cultural services are non-tangible, there is a long-lived tradition of using and benefitting from them. There is a strong and highly revered attachment between the communities and cultural services they receive from the landscape (Table 5.3).

Table 5.3 Cultural ES ranked according to their importance

Cultural ecosystem service	Order of importance
Cultural	1
Spiritual	2
Sense of place	3
Tourism	4
Intellectual stimulation	5

It is mainly the cultural activities such as *intonjane* and *ulwaluko* (Appendix 2) which are quite popular with people and are highly respected. Both are initiation practices, the former for girls and the latter is for boys. *Ulwaluk*o for boys is not just a cultural ritual, but it is a practically necessary, if not compulsory, exercise to undergo among the local Xhosa-speaking communities, for it marks the much- revered transition from boyhood to manhood. There are certain herbs from the veld whose names are kept secret that are used to treat the boys during this process.

Regulatory and Supporting services

In contrast to provisioning and cultural services, regulatory and supporting services were not well understood by the respondents. Some of the services that people did not have knowledge of are carbon sequestration, climate regulation, waste decomposition and detoxification, purification of air and water, production of oxygen gas, soil formation and nutrient cycling. This made it difficult to rank them according to their importance.

A lot of effort was made by the researchers to explain what these services are. Interviewees demonstrated a better understanding of purification of water, soil formation and production of oxygen gas than other services, such as carbon sequestration, climate regulation and waste decomposition. It was observed that Regulatory ES, which involves water, soil and air for breathing, are closer to human functioning than Supporting ES.

There are a number of benefits from ecosystems that respondents knew were important, but they could not explain how exactly they come to be, e.g. ESs such as clean water, clean air, waste decomposition and nutrient cycling. They did not know that ecosystem elements such as soil and wetlands help to clean water. Although all the informants emphasised the importance of air for human life, they were not aware that the supply of air to breathe is a service dependent on the functioning of the ecosystem. Largely, respondents did not take these services as benefits from the ecosystem; rather they reported that they had been thinking that these things were created by a higher power.

In spite of the challenges that informants demonstrated in trying to look at nature within the ecosystem service framework, they demonstrated rich knowledge of elements of nature, i.e. natural resources. They made, for instance, a long list (Appendix 3) of wild animals (e.g. caracal or lynx, porcupine, civet cat, spotted hyena, reedbuck, mole, rabbit, jackal, meerkat or mongoose), birds (plateau birds, ravens, hawk, hem bird, shepherd birds, Southern ground hornbill, owl, vulture), reptiles (leguaan, lizard, snakes), and invertebrates (earthworms and others like spiders, lice, locust). ***Some of these ecosystem elements were considered to be providing ecosystem disservices***. Ecosystem disservices are services that undermine the well-being of human beings (Dunn 2010; Shackleton et al*.* 2016). Examples were given of snakes and spiders that bite people, jackals and spotted hyena that eat livestock, locusts and moles that eat vegetables, and owls that are associated with witchcraft and bad luck. On the other hand, rabbits and porcupines provide aesthetic value. Their skins and quills respectively are used as ornaments to decorate rooms. A mongoose was seen as useful in that its skin is used for medicinal purposes.

In a study in Southern England on the degree of people's recognition of various ecosystem services in in a river drainage area, Burgess, Clark and Harrison (2000) showed some interesting parallels with our results. They collected data from a sample group that comprised farmers, local officials, politicians and researchers using survey and focus group techniques. They used a simple ranking technique to measure the degree of informants' recognition of ecosystem services. They grouped the services into three categories: (a) invisible services (e.g. uptake of carbon dioxide by plants, contribution of weathering to soil fertility, nitrogen uptake by leguminous plants), (b) visible services (e.g. rainfall, wild plants, and wild animals), and (c) human activities in nature (e.g. silence, opportunities for hunting, and other opportunities to enjoy nature) (Burgess, Clark and Harrison 2000). The researchers found that the ecosystem service concept was new to most informants, including those that had a natural science background, such as local environmental officials. Most of the informants demonstrated a higher degree of recognising visible services, followed by invisible services, and lastly, human action in nature (Burgess, Clark and Harrison 2000).

5.2.2 Ecosystem challenges and management practices at Mahlungulu and Mgwalana

Historically, the villages have suffered environmental challenges, such as strong winds that cause damage to houses and result in high evaporation from crops and soil. Additionally, ***invasive weeds*** such as *tyhungu*, a thorny shrub that invades grazing lands, have been problematic. Cattle and goats do not eat this weed, so it outgrows grass and other shrubs that livestock feed on. Another invasive weed is black wattle. Table 5.4 lists the ranking of the ecological challenges according to the villagers.

Another problem is the ***shortage of water*** resulting mainly from drying up of springs and dwindling rainwater quantities. Although there has been a record of occasional meteorological droughts such as the ones that occurred in the late 1960s, early 1980s and early 1990s, starting about the year 2000 the water condition of the villages has been progressively declining. The community is responding by digging wells and building brick walls around them to provide protection against damage and pollution by animals. Some families are also buying rainwater harvesting tanks for harvesting water off their roofs

Overgrazing of rangelands is another problem that has progressively been increasing over the past 10 years. The problem of overgrazing is heavily associated with the shortage of rainwater, and in some cases by overuse of some areas because of lack of herding or rotation of areas used by the animals. The community of Mgwalana has put in place rules that prohibit indiscriminate veld burning; however, there are no effective enforcement mechanisms in place.

Table 5.4 Ecological challenges ranked according to the magnitude of their effects to well-being

Ecosystem service challenge	Ranking
Water shortage	1
Overgrazing	2
IAPs	3
Soil erosion	4
Water pollution	5
Littering	6

Another ecosystem problem is ***soil erosion***. There is widespread understanding of soil protection and erosion in the community. The interviewees explained that although soil erosion has been occurring since time immemorial, its incidence has recently increased, coinciding with years of drought and the ongoing phenomenon of erratic rains. Late and erratic rains are blamed for causing drying and low growth of grass, phenomena that significantly lead to dry soils that erode easily. Crop farmers especially have experienced soil erosion on their arable plots, and they have mainly dealt with this problem by making contour ridges on the plots.

Littering, especially of streams and rivers*,* is a relatively new ecosystem problem. It was widely reported that women have recently developed a habit of dumping child nappies and sanitary material in rivers as a way disposing of them after use. And other community members are also using rivers and streams as dumping pits for their household refuse, including plastic materials. Individuals have already started to sporadically conduct stream cleaning exercises, in which they remove litter from river and stream banks. The respondents said they would like the municipality/government to employ people in projects to clean the river and stream banks. And others expressed the idea that the community can start to organise itself and start water cleaning campaigns in which different sections of the village get to be assigned to clean certain parts of river and stream courses according to their location.

IAPs

Black wattle has been growing on the villages' arable lands and rangelands for many decades. Until recently, the community has been seeing black wattle as a useful natural resource. The trees provide villagers with poles for building houses, kraals, fowl runs and pigsties, as well as wood for fire, and shelter for their livestock when the weather is cold. All these are useful ecosystem services. Thus, local people have perceived the black wattle trees as valuable elements of the ecosystem.

From the time of the arrival of black wattle (1950s determined from aerial imagery) to the 1980s, some members of the community started several efforts to propagate the tree by taking seedlings from the forest and planting them in their own lands. Until very recently, the local people were not aware of the reality that the existence of black wattle was causing critical ecosystem disservices, such as invading rangelands and arable lands, as well as causing groundwater shortages.

The knowledge that black wattle uses groundwater and hence contributes significantly to drying of water sources, especially springs and wetlands is not only new to local people, but they were given this information by external agents including government and researchers. The implication is not just the existence of differences relating to knowledge between the locals and policy makers, but fundamentally that these differences get reflected in, and significantly shape, how the people give meaning to the value of intervention efforts to remove the wattle, especially through the government-sponsored WfW projects. The WfW programme is loved and credited by many, not so much for eradicating wattle bushes, but for creating employment for the unemployed local poor people.

However long before the arrival of wider based knowledge about the black wattle, the communities had already observed that black wattle was progressively colonising their arable lands. This became very conspicuous, especially from the 1990s. Although this posed a direct threat to agrarian activities, it coincided with the time of growing de-agrarianisation which has seen mass fallowing of arable lands, especially in rural Eastern Cape. Reasons for de-agrarianising are multiple, including shortage of rain, shortage of fencing, shortage of mechanisation services, and wider upstream and downstream agro-value-chain constraints that ultimately minimise profitability by smallholder farmers.

Some of the perspectives of the state of the natural resources and general environment are not backed-up by actual records. For example, the notion of 'incessant dry spells' is not supported by the meteorological records for Cala (about 14 km from Mgwalana). Based on the long-term (>50 years) of rainfall data, the expected mean annual rainfall at Mgwalana is 680 mm (Schulze 2007b). Since 2000, the NPP of Mgwalana, as determined by the MODIS PsnNet product (MOD17) has remained relatively constant, without any discernible trend (Figure 5.2).

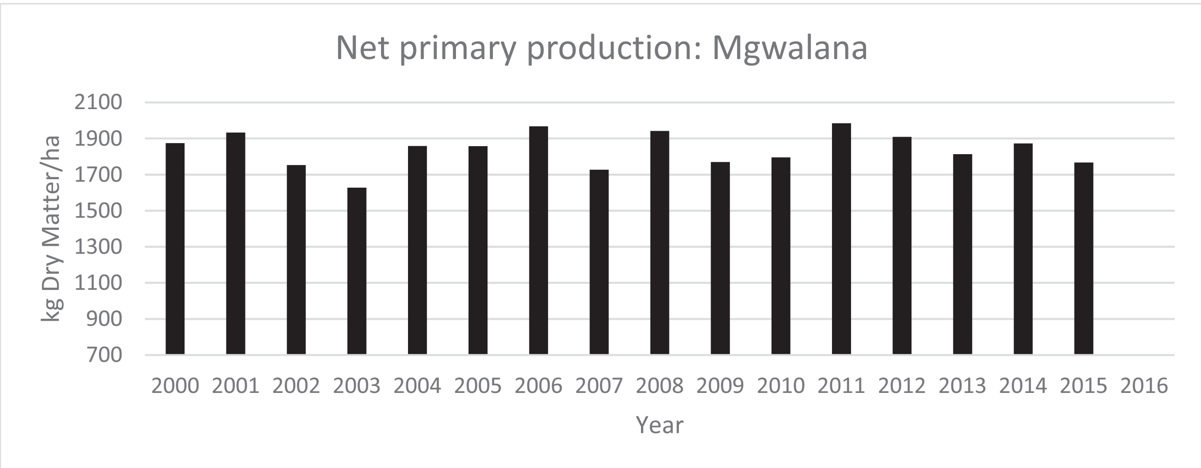

Figure 5.2 NPP in the unimproved grassland at Mgwalana

5.2.3 Aspired ecosystem futures at Mahlungulu and Mgwalana

Inquiring about aspired to ecosystem futures is a concept we drew from Scenario Planning which "involves thinking about a wide range of plausible futures, including both well-known trends and key uncertainties, and using this information to generate a set of storylines that can guide decision making" (Bennett et al. 2005).

When a response on aspired ecosystem futures was given, we followed up by asking who they thought was responsible for making the environment to be in the desired state. Further to this, we asked how they thought the person or organisation responsible can work to make the ecosystem be in that aspired to state. The effect of these questions was that they helped the respondents to hypothesise with a consideration of practicality in mind.

There are at least two important things that the local people aspire for improvement in their natural environment: water sources and grasslands. ***The majority of the respondents mentioned that they want availability of water in rivers, streams and springs to improve***. It is widely thought that water supply was far better in the past. The people identified two major causes to the current depletion of volumes in water sources. The first one was that rain has dramatically decreased in quantities. Secondly, rain is now very erratic and often comes in short-lived heavy bouts very late in the rainy season, hence a lot of it gets lost in runoff. Rain is understood to be a very critical component of the broader ecosystem.

The ***second aspiration of the community is to have green, healthy and tall grass back on the landscape again.*** It was reported that in the past there used to be abundant tall green grass in the veld. The grass has historically been used for thatching roofs because it used to be tall. A perennial grass species (*Cymbopogon plurinodis*) that is suitable for thatching was reported to be decreasing in quantities and there is widespread fear that it will soon disappear and no longer be a resource for roof thatching.

Responsibility to make this happen was reported to rest both on the local people and the government. The interviewees noted that people can look after grass in several ways. They can practice rotational grazing so that no portion of the grassland is overgrazed. Local people can also contribute by preventing random burning of the veld. The veld should be burnt every two years, and then rested for a year.

Other interviewees reported that the government can assist by giving fencing material so that the people can divide the veld into camps to allow rotational grazing. It is believed that rotational grazing makes it easier for livestock owners and other community members to observe and monitor the grass than what happens in free-range pasturing practices, which are currently utilised in the villages. Respondents said the government can also appoint people to control veld fires because the villagers do not have enough expertise and the necessary equipment to deal with big fires. The community can assist by propagating fire prevention and management practices and rules among the local people.

The ***third aspired to ecosystem condition is fertile soils***. When people talked about local histories of farming, strong narratives of soils that used to be very fertile always dominated. When crop cultivation used to thrive in the past, arable lands provided a rich green landscape. The people say soil fertility was reduced by incessant dry spells that lead to bare soil and soil erosion.

The ***fourth aspired to future element is to reduce IAPs***. The people blame the plantations for providing shelter to criminals, livestock thieves and rapists. The desire to clear wattle trees was not as animated or passionate as other aspired ecosystem conditions such as increased water supply, revived pasturelands and soils. This is happening in spite of the reality that for the past five years the government has been intensively driving the wattle eradication agenda through multiple community engagement means such as public meetings, research projects and the WfW programme. Although there exists a strong sense of enthusiasm towards the WfW programme among the local people, such positive spirit is largely driven by the fact that it is offering employment opportunities.

5.2.4 Conclusions

The importance of lay/local knowledge systems in ecosystem management in the contemporary age cannot be overemphasised, particularly given the reality that the world broadly is pushing for adoption of a decentralised natural resources management tradition. Among others, this is manifest in the CAMPFIRE programmes (Gandiwa et al. 2013) which have in the past decade or so been implemented in various rural communities of southern African countries including Zimbabwe, Zambia and Botswana. CAMPFIRE suggests that with limited technical and professional assistance, local communities have the capacity to manage natural resources sustainably by leveraging their lay/local knowledge systems. In South Africa, there are multiple policies that speak to the need for an integrated decentralisation of natural resources management practices that are sensitive to and leverage local cultures, knowledge resources and customs. Such policies include the South African National Water Act of 1998 which encourages devolution of WRM to local catchment fora and the National Forest Act of 1998 which provides for the need to include local communities in matters of forest management (Fabricius et al. 2006).

Leveraging local human and knowledge resources is not in itself the silver bullet. Lay/local knowledge systems often find it difficult to respond to slow ecological processes such as soil erosion, vegetation changes and climate change (Fabricius et al. 2006). Moreover, largely because of its heavy reliance on personal experience, lay/local knowledge might find it difficult to comprehend more indirect services such as Regulatory and Supporting ES. Perhaps researchers and practitioners need to consider means and opportunities to improve the capacity of local people to respond to various signals from the natural environment.

5.3 GIS mapping with communities

This exercise was conducted during the project's first year workshop and interviews were conducted in three villages in quaternary T12A between September to October 2014 and it was included as part of Deliverable 2. This work was conducted by Mr Adam Perry (a consultant during the first year of the project) and it included a GIS mapping exercise with key stakeholders in the Ncora catchments, Ward 3, Sahisizwe Local Municipality.

The workshop's aim was to determine what, where, and how land use practices are determined, what private contracting is taking place in the area (given the removal of wattle), and where grazing occurs. The ultimate goal was to conceive of future intervention strategies that could work for the area after the eradication of alien invasive species.

5.3.1 Mapping exercise introduction

In order to engage with the local communities, it was necessary to undertake a series of preliminary meetings and engagements with several levels of governance, including government officials (extension officers, local economic development officers), representatives of the communities, as well as traditional and elected leaders. This process involved several field campaigns to villages in the catchment as well as formal meetings with the residents of Mgwalana (quaternary catchment T12A). As one of the primary aims of the project was to assess the productivity of land after the clearing of IAPs, it was necessary to identify those villages where actual clearing of wattle had taken place. This assessment was carried out by obtaining the GIS coverages of clearing activity from the East London offices of the DEA (Figure 5.3a and 5.3b for T35B and T12A), followed by locating the areas within each of the catchments where recent wattle clearing had occurred.

5.3.2 Background information on Mgwalana village (T12A)

This village is within Ward 3 of the Sakhisizwe Local Municipality. Two key contacts at WfW in East London, Mr Andrew Hope and Mr Michael Kawa, had indicated that large areas of wattle had been removed (Figure 5.3b). The team therefore determined that Mgwalana village was closest to these areas where wattle had been removed and worked with the local *Ibodhi* (or chairman/ representative who liaises between community members and outsiders) and the local *Usibonda* (Headman) and the Chief.

Representative members of the community with an interest in grazing and invasive species removal were invited to social learning engagements at scheduled workshops in October. The uses of wattle included: (1) effective and free source of fuel in making fire; (2) poles for fencing; (3) building of local animal enclosures (*ubuhlanti*). Alternatively, some negative points of view were expressed which include: (1) wattle encroaches on local grazing fields; (2) animals are stolen or get lost in the deep thicket; (3) cultivation spaces are reduced by thicket encroachment. The community's fears that children would be lost in the forest, or succumb to criminals' bad intentions had led to the removal of all IAPs in front of the school.

5.3.3 Report of focus groups in T12A

The pre-workshop field trip (22-23 September 2014) and the preliminary meetings with local authority and with key stakeholders within the Ncora catchments, Ward 3, Sakhisizwe Local Municipality helped to establish the working relationships, identify key partners who would be willing to be a part of the focus group meetings in October, develop a mapping engagement plan and aerial maps of the area for the meetings (Figures 5.4).

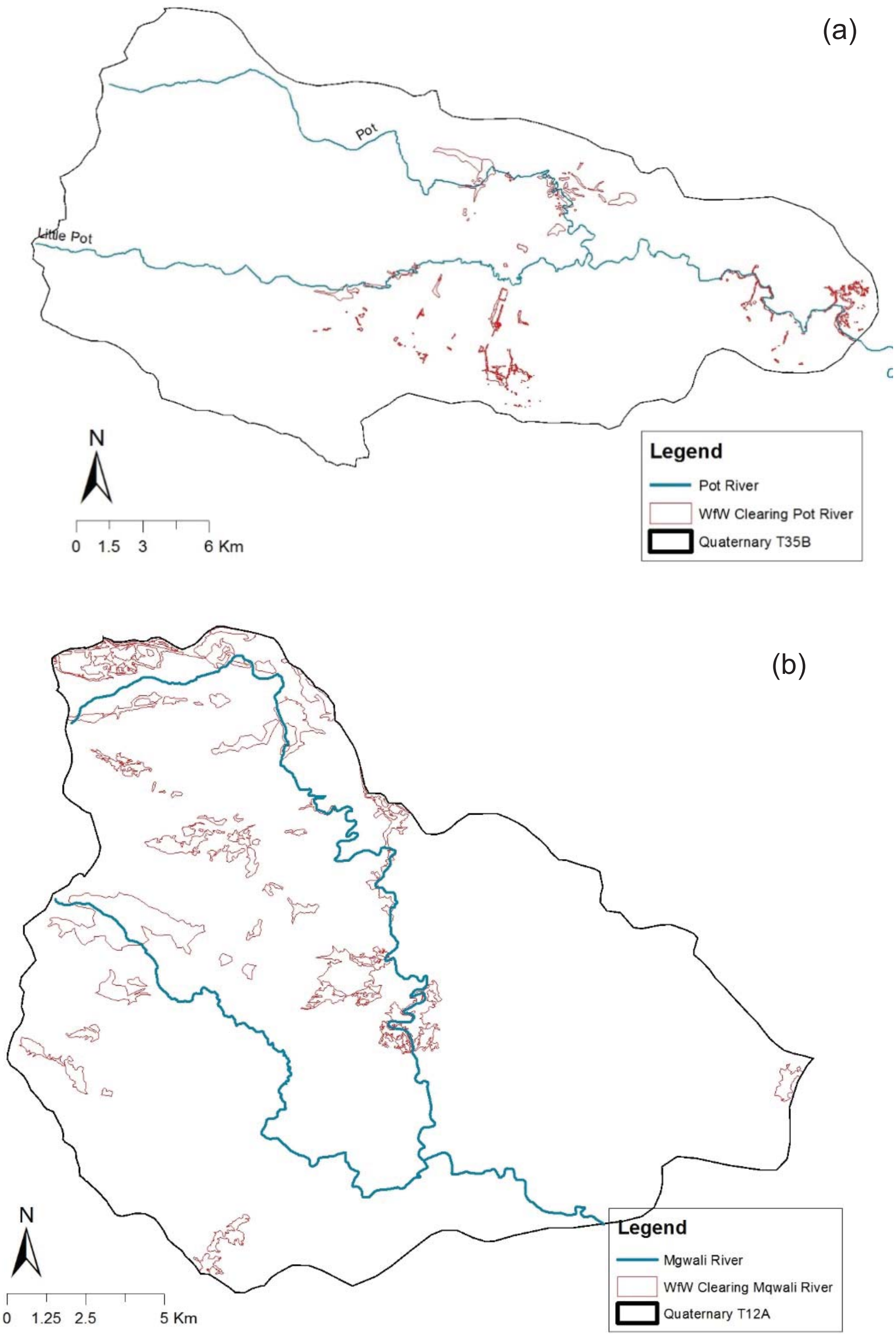

Figure 5.3 Area polygons cleared of alien vegetation according to WfW East London (shown in red) for (a) T35B and (b) T12A quaternaries.

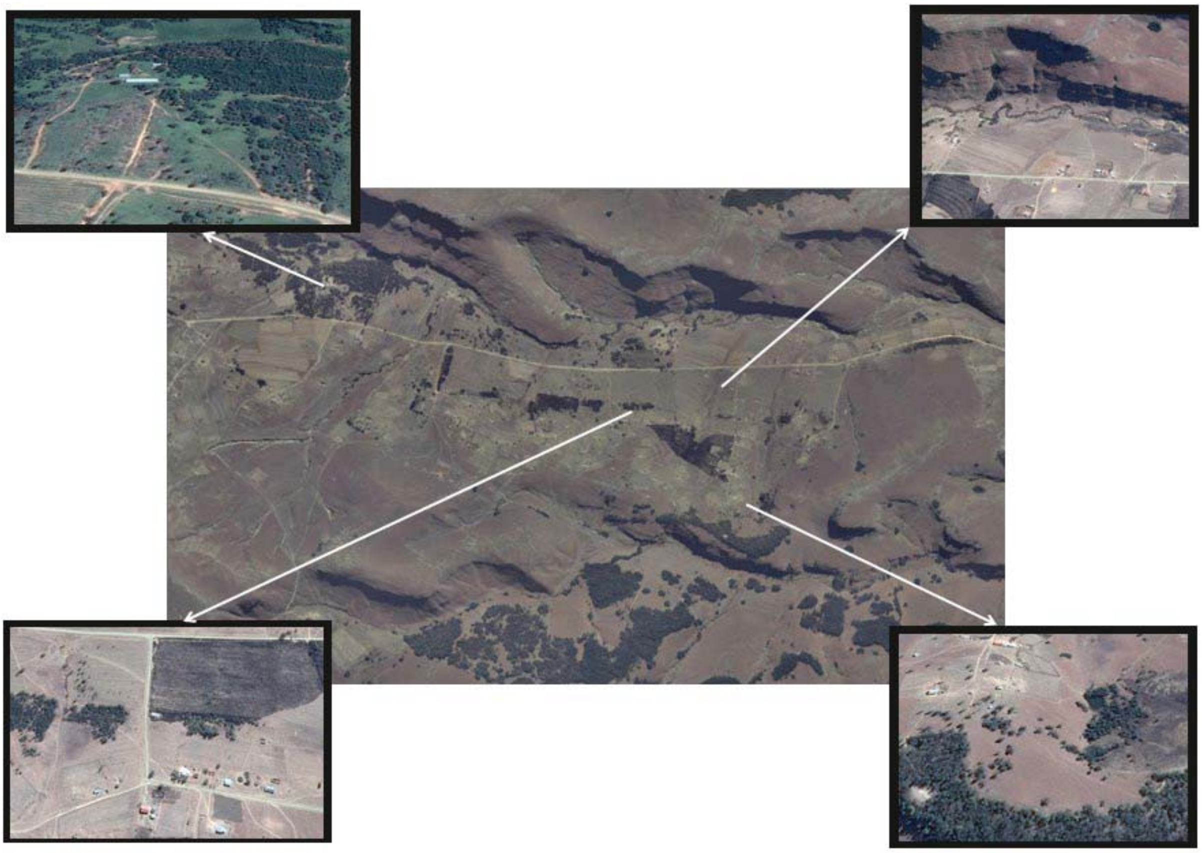

Figure 5.4 Orientation map of Mgwalana village showing location of school (upper left), fields and other landmarks for the meetings

Results of focus group meetings in Mgwalana, Skhobeni and KwaDike

During each of the three focus group meetings, the facilitators explained the overall objectives of the research initiative and the programme to the participants, clarifying that the focus was on identifying what happens after the removal of invasive species in terms of current land-practices, uses, and future ideas of how land can be used as seen by the community.

The meetings included people of diverse backgrounds representing youth, elder men, and elder women. There was a discussion to help people orient themselves on the map, and it was noted that the participants had little difficulty in understanding the map, or in determining where they were in the landscape.

General key points of note:

- Private parties interested in removing wattle, specifically those that might not have the community's interest in mind, are generally discouraged by the community and a community meeting is required to discuss the merits of any proposed project. In Skhobeni, the community does not often contest any removal project as local women (for stripping wattle) and local men (for loading the truck) are hired, in particular by a middle company supplying wattle to PG Bison, a timber processing company in Ugie.

- Anyone from the community has a right to access wattle as it is a communal resource, but not to engage in the sale of wattle to outsiders or companies without community input and a collective decision taken.
- Wattle is beneficial to the community and for those with animals as it provides shade for the animals. When the thicket is not too dense, animals can graze effectively.
- There is a problem with wattle encroachment in Mgwalana and Skhobeni as it is taking over farmland, residential areas, and animals are lost in the forests. There were complaints that the heavily thicketed areas (identified in Figure 5.5 as Communal Grazing Area #3, and Figure 5.6 as Private Lands #4 and #5), were areas where stock theft occurs. Theft generally occurs at night, with the culprits parking their cars on the paved roads and removing the goats, sheep and cattle via the thicketed wattle forests to the escape vehicles. Skhobeni animals are taken across the paved road to KwaDike to graze (left section of Figure 5.6).
- The local municipality and councillor assisted with removing wattle near Mgwalana School in order to improve the safety of school children. There were fears of potential crime and rape of children within wattle thickets while travelling to and from the school, in addition to fear of school children engaging in bad behaviours such as taking drugs while hiding in the forests.
- The community identified grazing camps, which are important in protecting stock and for rehabilitating overgrazed lands, on the map.
- Communal resources that are important assets needing protection were highlighted. Areas for potential rehabilitation (e.g. Private Lands #4 and #5 and Communal Area #5 which are encroached by wattle) were noted on the map.

> The aerial maps were effective in understanding the dynamics of the area, and in generating discussion about future ideas of intervention and rehabilitation.

5.3.4 Results and discussion

An evaluation form was used at the end of the meeting to capture the learnings from the focus groups. Table 5.5 shows that the responses were similar across the three focus groups. Most respondents had not seen or used aerial maps previously. Everyone agreed that the maps were quite useful and participants recommended aerial maps in future engagements.

Six potential uses for cleared land were explored across the three villages:

(1) removing wattle thickets could lend itself to the cultivation of pine plantations;

(2) there is opportunity to improve grazing lands via planting better grasses, improving soils, and summer and winter grazing camps ought to be encouraged as potential strategies;

(3) after removing wattle, there could be an opportunity to reclaim older arable lands previously cultivated and/or acquire new lands for arable cultivation;

(4) better management of wattle forests for protecting one's stock (or commercial interests) could encourage opportunities for protecting against fire or further encroachment, as ideas enshrined in the 'Working for Fire' and 'Working for Water' programmes;

(5) after wattle removal, there is potential for opening up of land for residential housing and commercial buildings;

(6) there could be some opportunity for community projects to occur such as space for football playing fields.

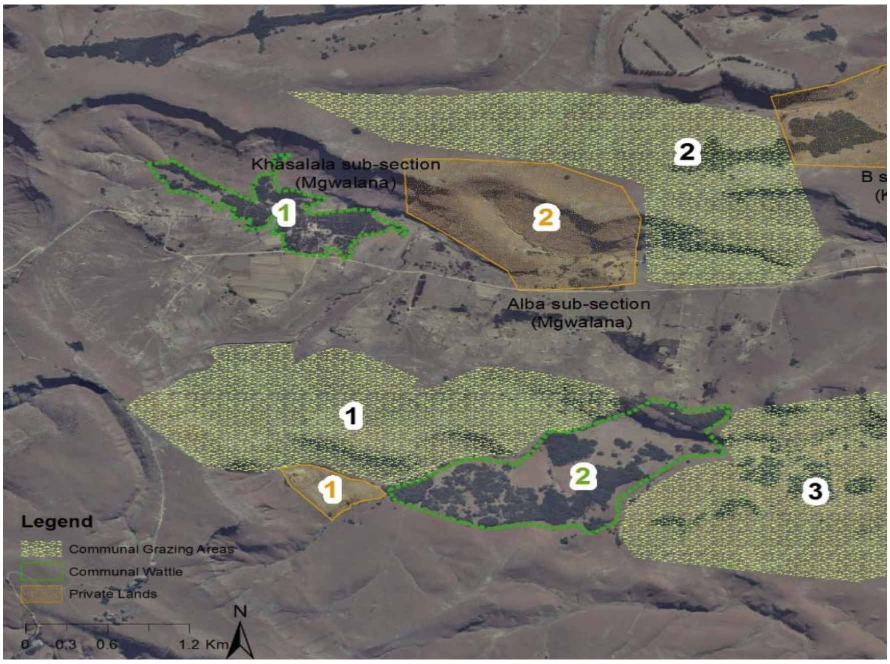

Figure 5.5 Areas identified by first focus group participants in Mgwalana area. The numbers identify individual areas under communal grazing, communal wattle and private lands, some of which are mentioned in the text. Note some of the areas serve more than one function in particular the communal grazing areas have some wattle that is harvested.

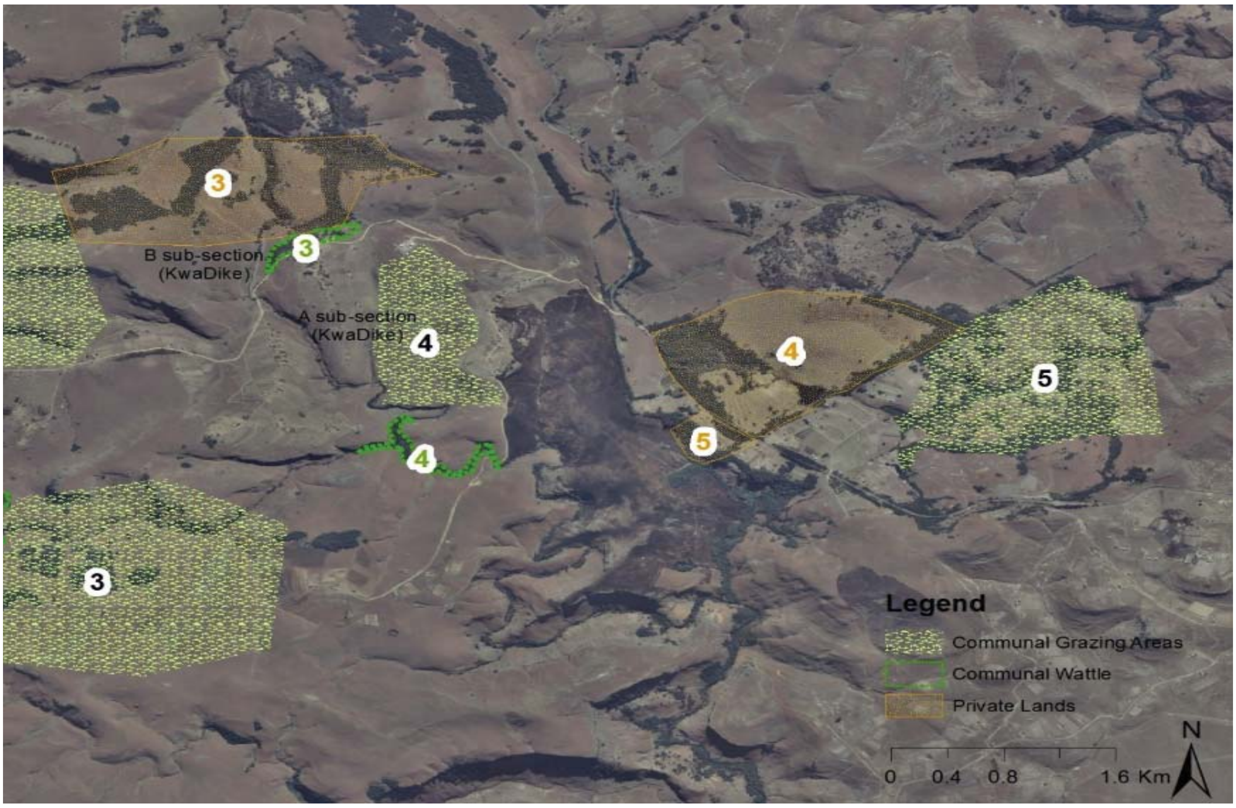

Figure 5.6 Areas identified by first focus group participants in Skhobeni (right section) and KwaDike (left section) areas

Summary of some of the recommendations for managing grasslands and for WfW programme are as follows:

(1) Rehabilitation ought to be conceived in terms of some of the social concerns facing communities instead of simply for improving soils or planting grasses. Wattle is important as a resource in some areas e.g. for fencing, construction, as a fuel source. Protecting and improving grazing seemed to be the most important aspect of rehabilitating lands after the removal of wattle. Some villages, such as Skhobeni, would be interested in the potential of thinning wattle to bring back healthier, more robust grasses.

(2) There are potential commercial partnerships which need to be embraced and supported given there are strong connections already taking place with PG Bison for some villages.

(3) There is interest in communities in grazing camps that can be used over winter and summer in order to prevent overgrazing. There was a lot of support for improving the current soils, grasses, and strengthening pasturing lands.

(4) Across all three sites there was some interest to remove wattle and have pine as communal resource that could be used for homestead uses in construction. Revenue generation via the sale of pine to PG Bison was conceived as an additional strategy for livelihoods.

Table 5.5 Responses to the questions by the respondents in Mgwalana, Skhobeni and KwaDike

	Mgwalana	Skhobeni	KwaDike
Q 1: Respondent knows about WfW or Working for Fire (WfF) programme			
• Yes	6	2	0
• No	0	4	6
Q 2: Respondent knows of other programmes that remove IAPs (such as private companies, e.g. PG Bison)			
• Yes	0	6	6
• No	6	0	0
Q 3a: Respondent has seen aerial maps or mapping similar to that conducted in the workshop before			
• Yes	0	0	0
• No	6	6	6
Q 3b: Respondent found the mapping useful in discussion			
• Yes	6	6	6
• No	0	0	0
Q 4: Respondent found mapping exercise useful for describing the area			
• Yes, highly useful	6	6	6
• Yes, somewhat useful	0	0	0
• Maybe	0	0	0
• No, not useful	0	0	0
Q 5: Respondent recommends using maps in future engagements			
• Yes, highly recommended	6	6	6
• Yes, with some changes	0	0	0
• Maybe	0	0	0
• No	0	0	0
Q 6: What learnings did you gain from others			
• Pine plantations could be an option post-clearing	4	3	2
• There are opportunities to recover land for housing/commercial purposes	1	1	1
• There are opportunities for improving grazing lands	2	5	4
• There are opportunities for improving community spaces, e.g. football fields	1	0	0
• There are opportunities for improving lands for arable purposes	2	1	4
• Opportunities for employment	0	0	1

5.4 Grasslands after wattle clearing: business opportunities for villages affected by wattle

5.4.1 Introduction

The project assessed the natural resources of two villages that were impacted by the invasion of large areas of their communal style grazing land by black and silver wattle. Through the

WfW Programme of the DEA-NRM, several hundred hectares of invaded area were cleared of the wattle. This study has developed an improved understanding of a CSES that comprises the mixed farming system under communal tenure, and how recently-cleared areas are contributing to household livelihoods. Mixed farming, the dominant farming system in this geographic area, comprises the production of maize, vegetables and livestock products, all with direct benefit to household livelihoods. In an effort to understand the complexity, the project team has used a range of ecological and social lenses to view the landscape productivity, the water use and the linkages with household income. These lenses have focused on the direct impact of the wattle on water use by the trees, the usefulness of the wattle itself as fuelwood and as timber for the chipboard industry, and the alternative uses of the cleared areas.

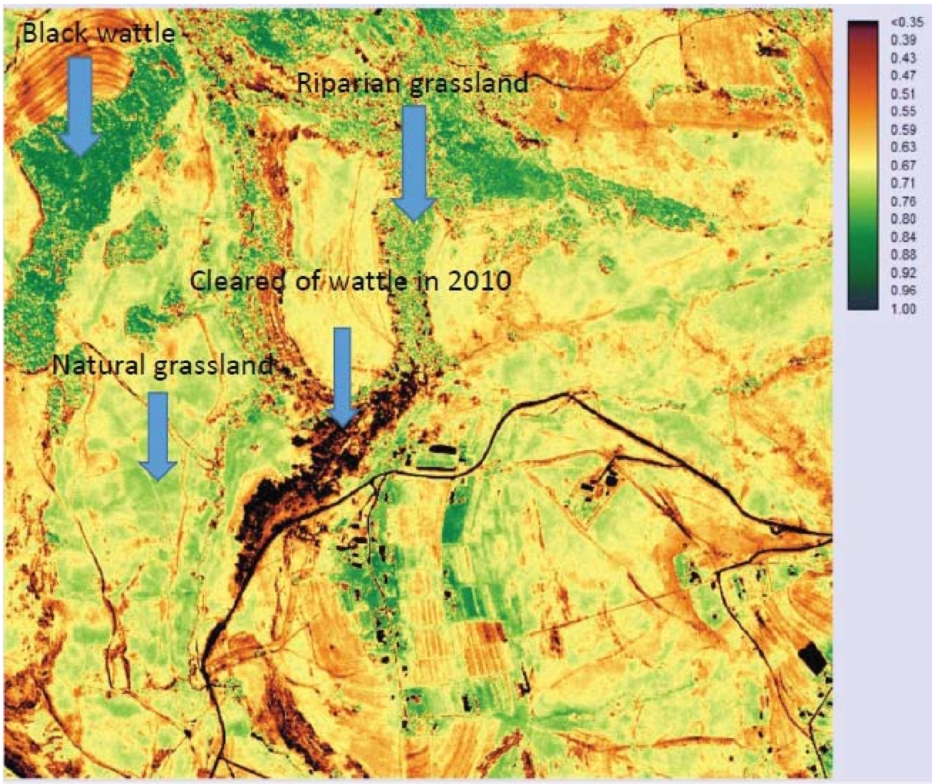

Figure 5.7 A very high resolution NDVI (Digital Globe 1m: March 21, 2017) of a portion of the village of Mgwalana, showing the extremely low NDVI values (brown colour) for the area cleared of wattle in 2010. This is further evidence of the danger of clear-felling without adequate post-clearing treatment.

The rapid clearing of wattle has different effects in different landscape components. On steep slopes, the clear-felling results in severe erosion, with little re-growth of the preferred grasses (Figure 5.7). Because of a lack of adequate fencing in these areas, livestock rapidly move onto the cleared areas, taking advantage of the extra nitrogen that is held in the soils after many years of wattle growth (wattle is a nitrogen fixer). Following soil analysis of selected areas that had been cleared and comparing them with un-cleared areas and native grasslands (Gwate et al*.* 2018), it became clear that the simple clear-felling was the least desirable approach. Following from this, we undertook to explore options other than clear-felling for wattle control. These included determining the LAI under a gradient of wattle density (Gwate et al*.* 2016) and the determination of grass production under the wattle canopy.

5.4.2 Community workshops and learning/access to markets

Year two workshop: Information exchange workshop on wattle harvesting and entrepreneurial opportunities 12 April 2016

This section provides a summary of an information sharing workshop that we conducted on 12 April 2016 at DM Skosana Senior Secondary school in Ward 9, Sakhisizwe Local Municipality. Preceding research activities had revealed that wattle trees were causing problems to local communities including invasion of arable and grazing lands, in the process depleting livelihood opportunities. There are entrepreneurs that harvest and sell wattle to PG Bison and the DEA was implementing the WfW programme in the district. However, people did not know about these programmes. We invited these companies and DEA to talk about their programmes.

The meeting was attended by Mr M Kawa, a senior manager at the DEA, Mr Ndongelo, an independent entrepreneur who trades in wattle, municipal and traditional leaders. Dr Palmer outlined the history of wattle trees in South Africa. He explained how the trees changed from being an asset to a liability that invades arable and grazing lands, as well as sucking ground water. He explained ways of eradicating wattle including biological techniques. He said that there is need to facilitate re-growth of grass and indigenous trees on the cleared land parcels in order to restore ecological health of the landscape and revive agrarian livelihoods for people.

Mr Kawa explained DEA’s wattle eradication programmes (Figure 5.8). They include Working for Forests, Working for Energy, Working for Electricity and Working for Ecosystems. He explained the benefits of these programmes in addition to jobs for the communities including furniture make from wattle such as schools desks and caskets that are sold to bereaved households at subsidised prices (Working for Forests) and charcoal (Working for Energy).

Figure 5.8 Mr Kawa explaining how WfW programme gets implemented

Mr Ndongelo, an independent entrepreneur who cuts wattle from communities and sells it to PG Bison, explained the process, where PG Bison buys timber that is between 1.8–2.5 m in length and >3 cm in diameter. He offered to assist community members to become entrepreneurs by registering companies and getting contracts from PG Bison.

Year three workshop: Information exchange workshop on rangelands management and livestock marketing opportunities

Preceding data collection had showed that although people had free access to pasture and boasted much knowledge in livestock farming, they were not optimally benefitting from their livestock. The major problem was that they relied on a local market system which offered low prices. In response a knowledge exchange workshop that would address this problem was organised. The first part of the workshop involved taking four community members to attend a cattle auction organised by Meat Naturally on 16-17 May 2017 at Thaba Chicha in Matatiele. The second part was a workshop at Mgwalana focusing on rangelands management and livestock market opportunities.

Matatiele workshop: Learning exchange on rangeland stewardship, landscapes and livelihoods - The Meat Naturally model, 16-17 May 2017

This was a two-day learning exchange hosted by Umzimvubu Catchment Partnership Programme (UCPP) partners Environmental & Rural Solutions (ERS), Maloti Drakensberg Transfrontier Programme (MDTP), Conservation SA (CSA) and Meat Naturally Pty (MNP) in Matatiele. Day one showcased a locally developed grassland restoration model, which provides a framework for maintaining healthy communal landscapes and livelihoods through sound rangeland stewardship. The event formed part of the South African National Biodiversity Institute (SANBI) and Department of Science and Technology (DST) uMzimvubu Research, Development and Innovation (RDI) platform initiative, as well as a World Wide Fund for Nature (WWF) Nedbank Green Trust-supported freshwater security project implemented by ERS on behalf of the UCPP. Day two was Meat Naturally livestock auction at Thaba Chicha. Here participants witnessed the livestock marketing process in action. The auction sold 70 animals, generating R543 350 for 35 sellers, of which 31% are women. Average prices were around R15.62/kg.

Mgwalana workshop: How livestock utilise the landscape, market opportunities and land use change 18 May 2017

Dr Palmer presented on how livestock utilise the landscape and market opportunities. He explained several problems that result from the free-range grazing style that is prevailing in the village. He explained that failure to control cattle movements was leading to overgrazing of sweet grass and destruction of crops. He advised the community to fence their rangelands and divide them into rotational camps. Fencing allows for effective control of livestock movement, monitoring of pasture resources and veld fires. On marketing of livestock, he advised people to shift from regarding themselves as cattle owners to cattle farmers. He encouraged people to sell their cattle before they become too old. He explained how Meat Naturally conduct their auctions including that they want exclusively grass-fed animals, certified ownership of animals, and that they only come a village when they are assured of a minimum of 60 cattle available for sale. Dr Palmer concluded by telling the participants that Rhodes (his research team) were willing to assist the community with technical processes including branding and certification of animals, as well as mobilising Meat Naturally to come to the village and do an auction. A representative of the community who had attended the Meat Naturally auction then shared his experiences (Figure 5.9) which were extremely positive.

Figure 5.9 Mr. Nani explaining what he learned and observed at the Matatiele Meat Naturally auction

Ms Thantaswa Zondani (ARC; research team) presented on land use change. She explained that land use change refers to the changes taking place in how people use land. The aim was to get the changes that had occurred in land use at Mgwalana. Three major land use changes were found from the focus group discussions. First, crop cultivation is reducing in area cultivated because of many reasons including stray livestock that destroy crops. Second, grazing lands are becoming smaller mainly because some parts are being allocated for residence. Third, more land is being used for residence than before to accommodate increasing population. Lastly, expansion of wattle bushes is leading to disappearance of natural forests which were used for harvesting medicinal plants.

Evaluation exercise to determine the participants' learning showed that the biggest take-home was opportunities to participate in the wattle harvesting value chain as suppliers to PG Bison. Villagers are also interested in Meat Naturally conducting auctions in their village.

5.4.3 Alternative management strategies – thinning, board mill, carbon market

- **Thinning, rather than clear-felling, has been shown to be an effective option to improving grass production under the wattle canopy.** Very dense wattle stands can have a LAI of >7, equivalent to some of the highest LAI recorded worldwide. This almost totally eliminates the radiation necessary to drive photosynthesis, and results in a barren understorey. In wattle stands with much lower LAI (<2), we measured the cover of grasses, and identified the thresholds of wattle density that represented these conditions. The WfW programme would have to modify clearing protocols to achieve these lower LAI levels. In addition, biological control would have to reduce the seed-rain to enhance the efficacy of this new clearing process. Members of the research team are currently actively involved in negotiating these proposed changes with the DEA-NRM Implementing agents.

- The research team also engaged with the **PG Bison board mill at Ugie** where some of the wattle is currently being processed. The mill will take any wattle that has been felled and de-barked in the size range 3 cm – 50 cm diameter, and in lengths from 1.8-2.7 m. These logs, in wet condition, are then purchased at R270-300 per metric ton. PG Bison report that they will accept as much wattle as they can get. There is no limit as they want to keep their pine for cut timber. Any community that clear-fells wattle using the inputs from the DEA-NRM Implementing Agencies can then sell the timber to PG Bison. During a workshop between managers from DEA-NRM, ARC, Rhodes University, the communities from Mahlungulu village and a transport entrepreneur, all the options were presented to the villagers.

5.4.4 Meat Naturally and ACIAR

Through a high value beef partnership project (VBP), the ARC embarked on a journey to improve and develop commercial and communal-orientated smallholder beef farmers to produce high-quality free-range beef products that are cost-effective to meet the preferences of South African beef consumers. This project is funded by the Australian Centre for International Agricultural Research (ACIAR) to increase productivity and profitability of communally orientated smallholder farmers. The ARC, Stellenbosch University, University of Fort Hare, Provincial Departments of Agriculture, University of New England, National Agricultural Marketing Council, Department of Agriculture Forestry and Fisheries are the major stakeholders collaborating on the project. The project supplies free-range beef weaners to Cradock and Cavalier abattoirs who then supply Woolworth's. It is ARC's responsibility to provide skills and training to the farmers that are willing to join the project. Farmers are trained and supported to achieve a sustainable beef production system that enables their cattle to meet the free-range market specifications. This includes assistance from the project team in forward-planning the sale of their cattle and making decisions about the cost-effectiveness of choices such as free-range markets, reducing the stocking rates on their farms, providing supplementary feeding to cattle to increase their growth rates and reduce age at sale, culling non-productive breeding cattle and implementing rangeland remediation plans etc.

Opportunities for beef value-chain project

There was an interest shown by South African retailers in marketing free-range branded beef products. ARC, as a prime stakeholder had the opportunity to meet and brief farmers about the VBP project and recruiting farmers that have the capacity to meet the market specification. The VBP project requires that farmers meet the following criteria before joining:

1. Must at least have 30 breeding cows on the farm;
2. Must be willing to sell cattle up to the age of 3 years;
3. Must control where the animals graze;
4. Must have high grade Brahman cattle or dairy breeds;
5. Must be willing to follow Woolworth's criteria for cattle that meet free-range beef specification;
6. Communal farmers' association is managed and governed.

5.4.5 Business plan for village

In order to develop a viable business strategy for the villages, it is essential that the issues of trust be resolved and agreed upon by the communities prior to any steps being taken to establish a legal entity and appoint its office bearers. The *modus operandi* of the business entity will need to be developed in collaboration with community members, and the responsibilities of all office bearers clearly articulated. In addition, the expected outcomes from any business arrangements must be clearly articulated. The business plan below therefore presents, in bullet form, the steps that are necessary for the legal entity to be formed that can receive and disburse funds from the common resource. Wattle is one common property resource within the villages, and any financial benefits that accrue from its sale should be for the common good, or for those who actively participate in the process of removal and clearing. The DEA-NRM WfW programme will fund the clearing of specific areas, leaving the villagers with the opportunity to acquire further funds from the sale of the cut wattle. The financial returns from wool and livestock commodity sectors is also a significant product of the common property resource. As individuals own cattle and sheep, there are several ways in which the community can generate an income: 1) set a levy for the grazing and water that are used in the production of wool, mutton and livestock; 2) tax the formal and informal sale of all livestock products. We recommend that there is a monthly grazing levy charged for all livestock (sheep, cattle and goats), and that this is payable by each and every livestock owner. There should be explicit rules for defaulters. It is no longer an option to continue in the 'business as usual' model that has been the habit of communal residents throughout southern Africa. It is vital that the common pool resources (grazing and water) used to produce financial gains for individuals are properly managed and accounted.

The following steps are recommended:

- Establish a legal entity (Trust or CC) and prepare a framework, or set of conditions, for the management of common funds. The Articles of Association for the Trust or the CC should include a full description of the responsibilities of each office bearer;
- The community must agree on a constitution for the legal entity, as well as activities that must take place e.g. regular meetings of the trust, appointment of a bookkeeper, company secretary, auditors, appointment of office bearers who are capable and willing to call annual meetings and prepare and keep records (minutes and financials);
- Agree on common business principles – honesty, transparency, accountability, dialogue, regular feedback;
- Prepare and sign a livestock sale agreement with either Grass-fed Beef or Beef Naturally;
- Set of annual auction dates for large stock sales;
- Resource management activities
    - Appointment of a ranger responsible for maintaining the livestock register. The ranger would be responsible for confirming all livestock holdings and transactions, as well as being part of the rangeland assessment and management team. The job description for a ranger will include maintaining fences, gates, water points, firebreaks, etc.;
    - Ear-tagging of all livestock;
    - Registering of a brand, and branding of all large stock.
- Identification of potential sources of income from the common resource pool
    - Grazing fee on all livestock held;
    - Levy on all livestock and livestock products (wool, milk, skins) sold, including those sold internally through traditional sales.
- Identification of potential business partners:
    - PG Bison
    - DEA-NRM
    - National Wool Growers Association
    - Beef Naturally
    - Grass-fed Beef (ARC)
    - BKB Ltd (https://www.bkb.co.za/)
    - Cape Wool and Mohair

5.5 MCDA for prioritising clearing in Tsitsa River catchment

5.5.1 Background

In the final year of the project, a workshop titled 'Towards a Strategy for Management of Invasive Aliens for Tsitsa River Catchment: WfW Prioritisation Clearing Plan' was run with the aim to develop a spatial prioritisation of areas infested with invasives in Tsitsa River. The workshop was conducted on 23rd March 2018 with some of the researchers at Rhodes University who are working in the catchment and decision-making stakeholders (DEA, WfW, and Gamtoos Irrigation Board) who are involved in the Tsitsa Project run by DEA. The representatives of government departments and WfW implementation agencies were: Mr M Kawa (Manager, DEA: NRM); Mr Japie Buckle (Technical Advisor, DEA: NRM); Mr J Ngcengane (Manager, Gamtoos Irrigation Board); Mr C Hope (Quality Management, DEA: NRM).

The reason for selecting this catchment of Tsitsa River (the upper catchment of Mzimvubu River Figure 5.10) for this exercise is that it is an important Water Source Area in Eastern Cape Drakensburg (*Defining South Africa's Water Source Areas*, WWF-World Wide Fund for Nature 2013). Two dams are planned in Tsitsa River catchment by the DWS – Ntabelanga and Laleni Dams. However, there is concern about lifespan of the dams due to extent of invasion and highly erodible soils, and this is what the prioritisation plan is targeting. Le Maitre et al. (2016: Figure 5) estimated the reductions in the naturalised Mean Annual Runoff (MAR) by IAPs for Tsitsa River catchments (T35A-M) can be up to 5% per quaternary catchment. Removal of aliens and rehabilitation of grasslands also contributes to South Africa meeting the targets for SDGs 6 (Clean Water and Sanitation), 14 (Life Below Water) and 15 (Life on Land).

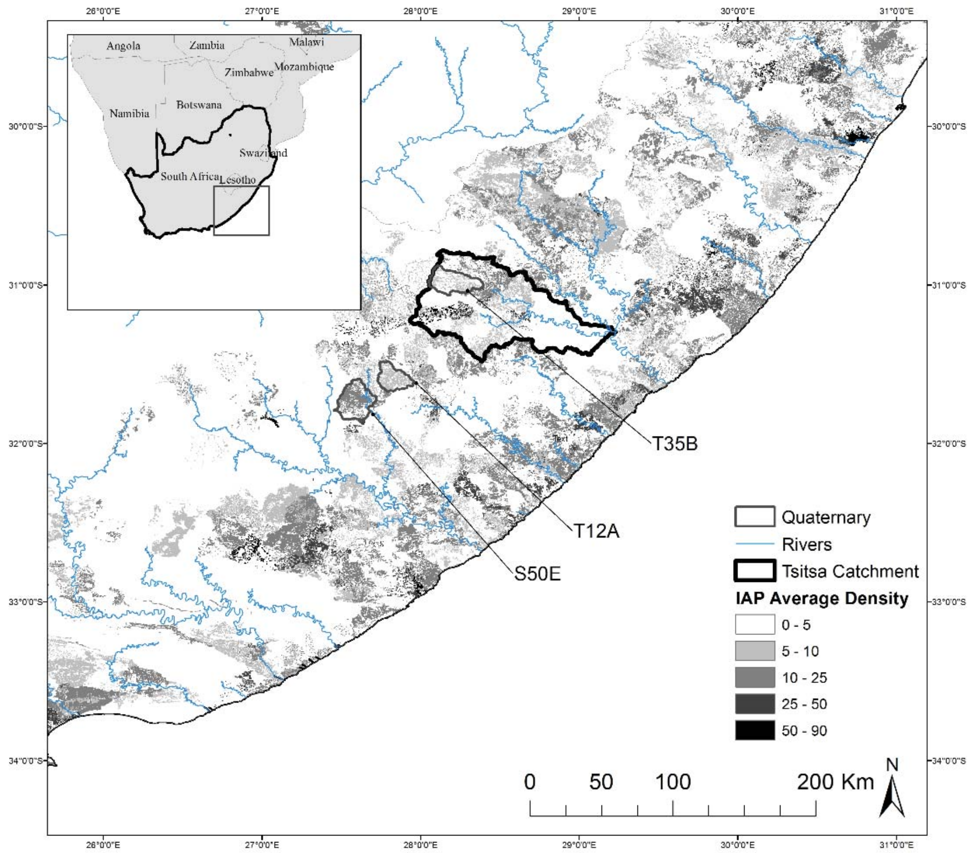

Figure 5.10 Location of Tsitsa River catchment in context of invasive alien density

The prioritisation of clearing of invasive alien vegetation was envisaged in terms of a cost-benefit analysis taking into consideration the above background. The benefits of clearing wattle include (but not limited to):

- improved biodiversity
- ecosystem services (water provision, improved grazing)
- logs for wood mill in Ugie (PG Bison)
- firewood and poles for communities
- new areas for crop cultivation, housing, schools

The costs of clearing are associated with:

- density of invasion (with higher invasion density leading to greater cost)
- management method costs (mechanical clearing versus biocontrol where available)
- accessibility to area (linked to management method used)

A previous analysis using MCDA for prioritising WfW clearing in the Western Cape was conducted by Forsyth et al. (2012). The analysis focused on prioritising quaternaries for primary catchments E, G, H, J and K) using 12 spatial datasets for high priority invader species for Fynbos, Succulent Karoo and Nama Karoo. The datasets ranked criteria by determining their relative importance for alien plant control operations through stakeholder workshops. The present study adopts a similar approach for Tsitsa River at a finer scale of 250 m pixels.

5.5.2 Methodology

MCDA aims to achieve multiple, conflicting objectives (criteria) in decision-making by transforming criteria to a common scale and then weighting them by their relative ranking / importance (Figure 5.11). The weighted sum value is then used to generate a priority list of actions. The criteria included, their weighting and classes were discussed and agreed upon in the 23rd March workshop.

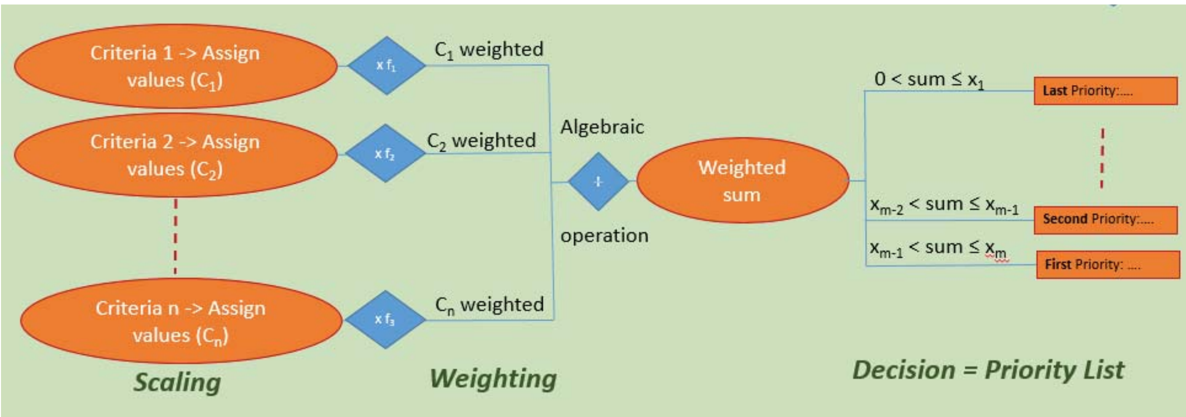

Figure 5.11 Flow chart of a generalised MCDA

For the analysis, four datasets were used:

(1) **Total IAP average density (%)** of the different IAP species was obtained from the National Invasive Alien Plant (NIAP) dataset generated by Kotzé et al. (2010). The data resolution of NIAP is 250 m and thus, all other datasets were generated at this resolution. The % average density for all IAPs ranges between 0 and 90, and these data were transformed to a common scale by assigning values to five range classes for the % average density (5: 0.001-10%; 4: 10-20%; 3: 20-30%; 2: 30-50%; 1: 50-90%). The five class breaks were chosen as they were similar to the natural breaks in the data, and the lowest density areas assigned the highest value because that represents the biggest return on investment in terms of cleared area for effort by WfW. The resulting map (Figure 5.12) shows gaps in data for quaternaries T35C, K, L. Dr Andrew Wannenburg has agreed to provide the newest version of the data once it is available before the end of the year.

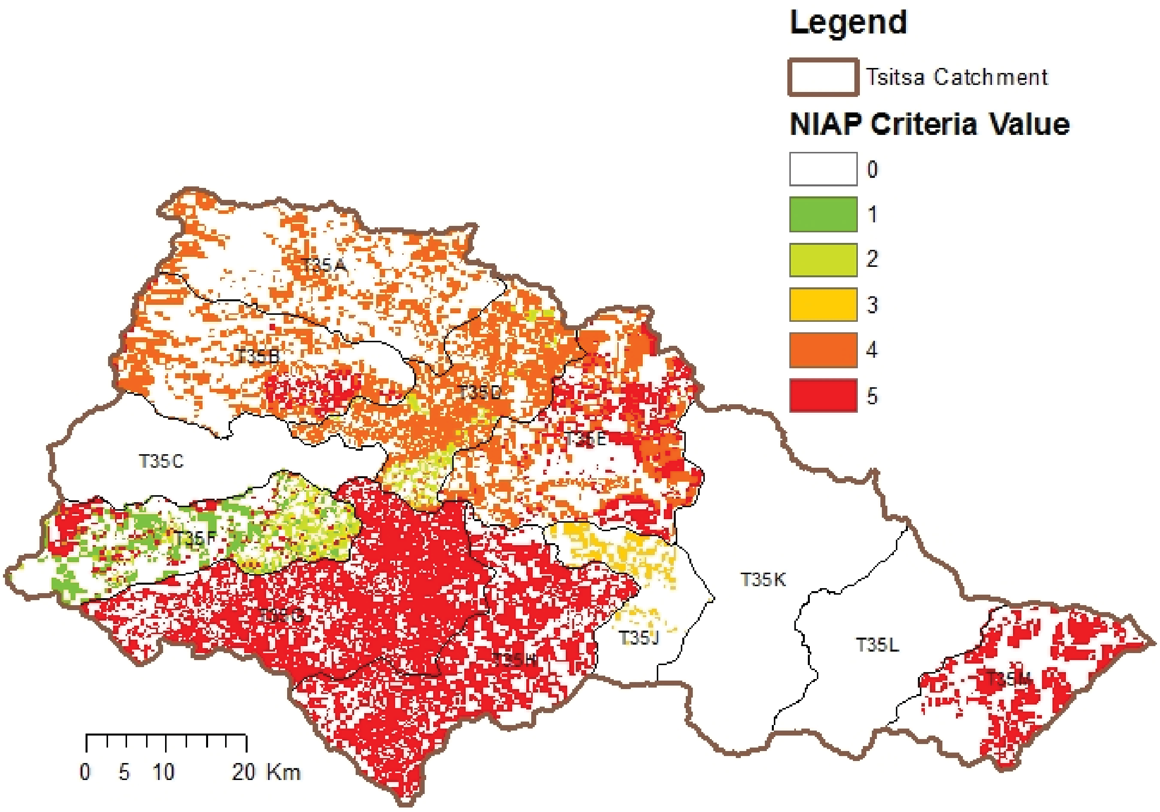

Figure 5.12 Criteria values for total % IAP average density that were entered into MCDA analysis. Note the missing data for T35C, K and L

(2) **Soil erodibility** K-factor was obtained from the 2007 South African Atlas of Climatology and Agrohydrology (Schulze 2007). The soil erodibility factor (K) is defined as the rate of soil loss per rainfall erosion index unit as measured on a standard plot. Erodibility factor classes suggested by Schulze (2007) were assigned values for MCDA (1: <0.13; 2: 0.13-0.25; 3: 0.25-0.50; 4: 0.50-0.70; 5: >0.70) to obtain the map in Figure 5.13. Highly erodible soils have higher rehabilitation priority for WfW programme and DEA (and were assigned highest value) because of the concern for lifespan of the dams, for supporting grassland rehabilitation and to alleviate the negative impacts of sediment on stream ecosystems.

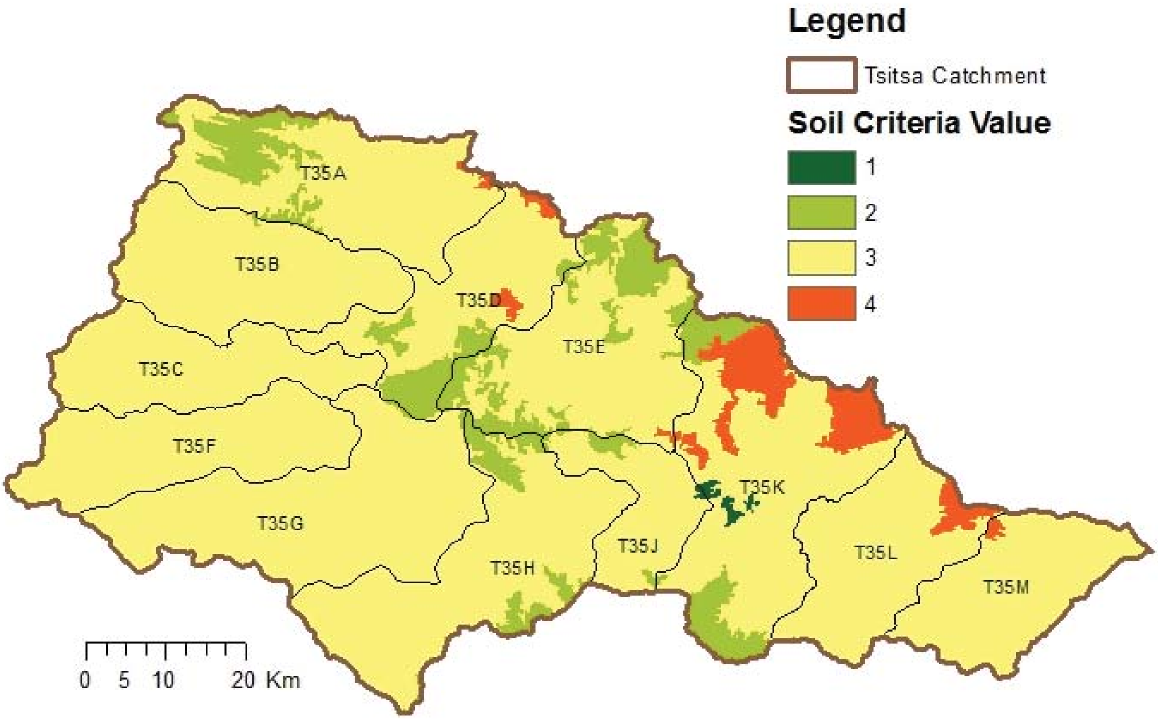

Figure 5.13 Criteria values for soil erodibility K-factor that were entered into MCDA analysis

(3) **Riparian areas:** Rivers are invasion pathways for invasive aliens. They are also biodiversity areas which are impacted by aliens and biodiversity does respond to restoration (Modiba et al. 2017). Stream order defines the location of a river in the landscape and was derived from SRTM 1 arc-second Digital Elevation Model (DEM) using ArcGIS Hydrology toolset (Figure 5.14, left). The values assigned to the river order were so that lower order rivers have higher priority (1: 6-7; 2: 4-5; 3: 1-3; Figure 5.14, right).

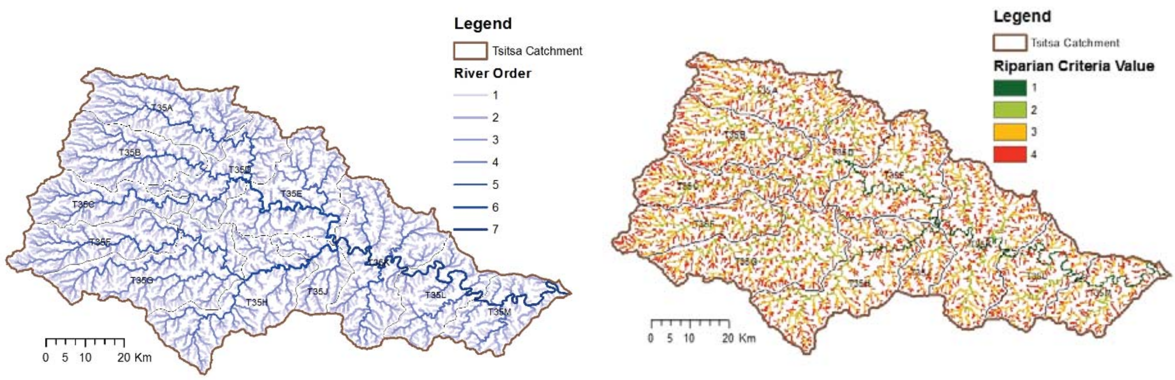

Figure 5.14 River order for Tsitsa catchment derived using ArcGIS Hydrology toolset (left) and criteria values assigned for MCDA (right)

(4) **Old lands / abandoned cultivation** areas were derived from overlap of two datasets: National Land Cover 2000 (NLC2000; dryland cultivation areas) and the National Invasive Alien Plant (wattle density data from NIAP; Kotzé et al. 2010). Previous research has shown that these areas have greater invasive potential compared to unimproved grasslands (C. Scorer, Honours project 2017, Rhodes University). The benefits derived from clearing the abandoned cultivation areas include their future uses by the community but primarily because of their potential for cultivation. In order to identify old lands, the following reasoning was used to identify if the dryland cultivation areas from NLC2000 were currently being cultivated or were old lands:

- Dryland cultivation areas with low density of wattle in NIAP = current cultivation
- Dryland cultivation areas with high density wattle = old lands

The resulting map (Figure 5.15) only identified 280 pixels or 17.5 km^2 of abandoned lands in Tsitsa catchment, but note this is an underestimation since the NIAP dataset has missing data (Figure 5.12).

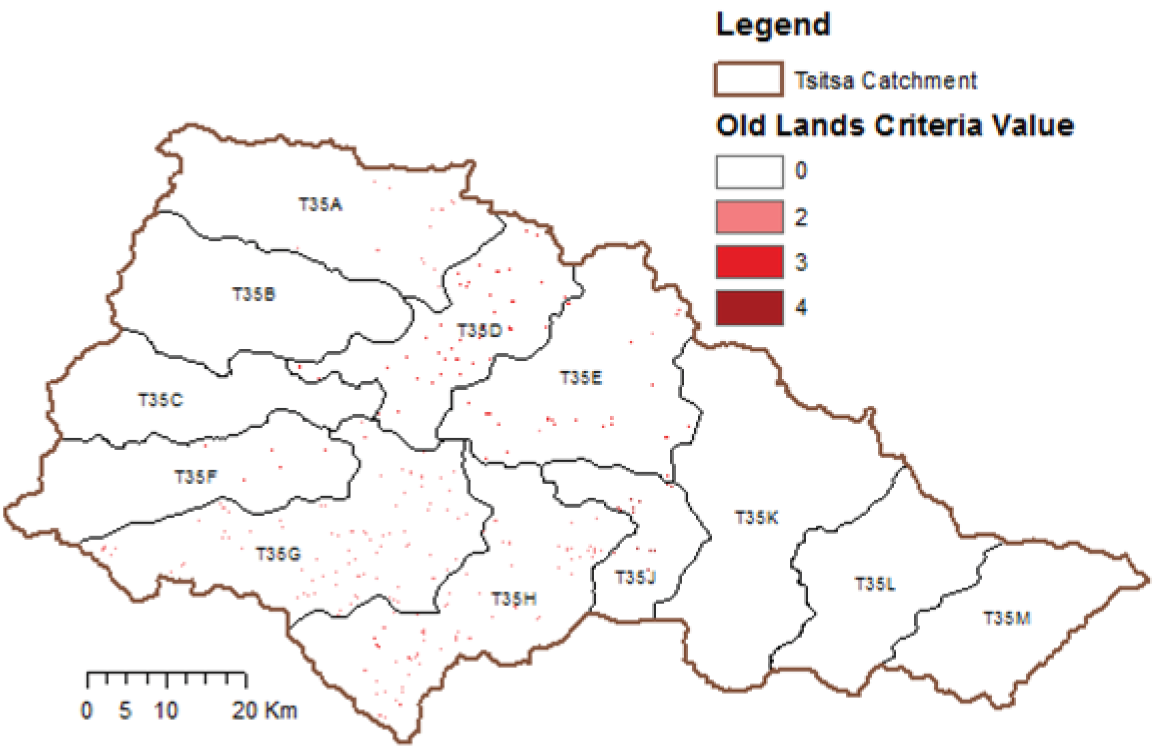

Figure 5.15 Location of old lands identified and their criteria values that were entered into MCDA analysis

Based on the survey results of the priority for the four criteria, the following weighting was used: NIAP and riparian zone (highest priority); old lands (second priority), and soil erodibility (lowest priority). Using these weightings, the priority clearing map in Figure 5.16 was obtained.

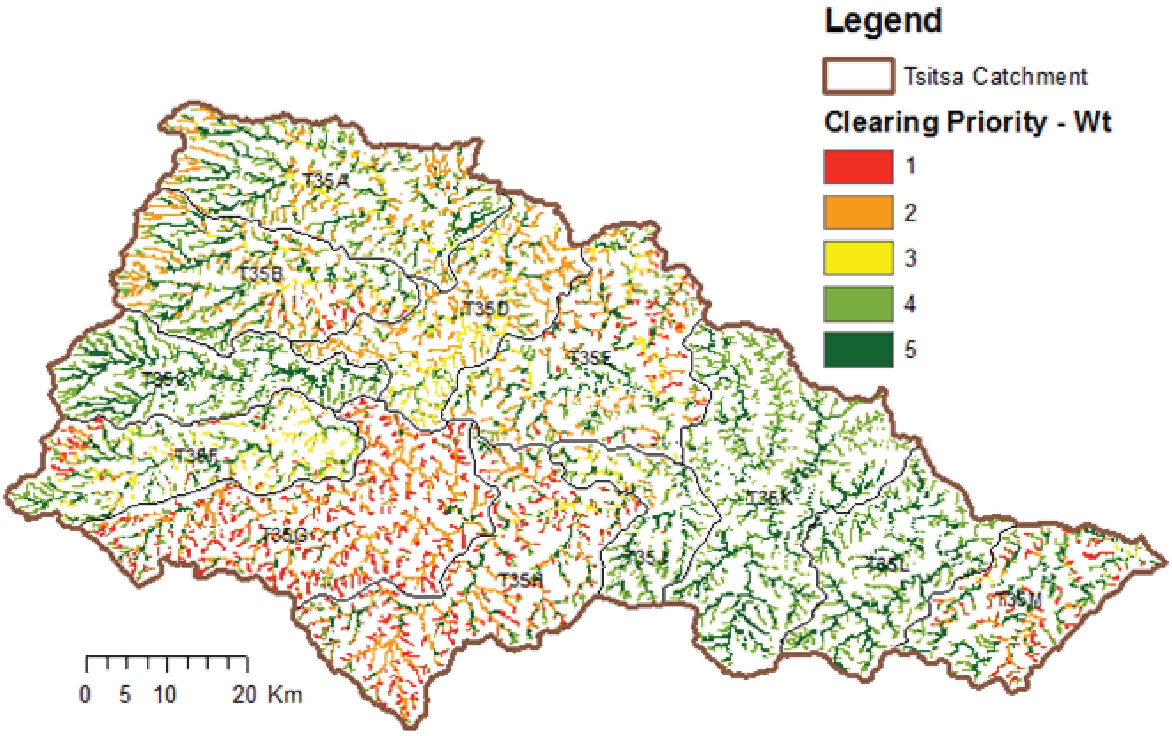

Figure 5.16 Clearing priority map for Tsitsa River with highest priority areas identified in red

5.5.3 Discussion

The analysis used in the MCDA analysis was based on a return on investment thinking towards clearing of invasive aliens for various benefits that the river and the community can gain including: improved biodiversity; ecosystem services (water provision, improved grazing); new areas for community's use (crop cultivation, housing or schools and/or potential for community based commercial plantations for supplying logs to PG Bison). The priority clearing map is not finalised as an updated version of NIAP needs to be obtained from the DEA, and additionally, for the results to be used by WfW, a budgeting tool needs to be developed.

One limitation of the MCDA analysis conducted here is that it utilised spatial data. However, there is potential to include data that is not available as spatial data but for which spatial surrogates might be available. This needs to be investigated in future analyses.

5.6 Project impact table

The activities highlighted above in terms of the project's impacts and interactions with the communities are summarised in Table 5.6.

Table 5.6 Summary table of field and workshop activities conducted under the project

Date	Activity – Workshop/ Dialogues/ Meetings	Aim	Participants	Outcome
Year 1 field trips	Field trips to S50E, T35B and T12A	Field sites selection and initial surveys	Villagers in the 3 quaternaries	Relationship building and spread information about project
Year 1 workshop	Workshop in Mgwalana, T12A	Use of Participant GIS and aerial images	Community groups, agricultural extension officer, Ibodhi and Ward Committee Representative	Developed relationship for work by students in communities Understand and map use of land and practices employed for irrigation, fire, grazing, and clearing by communities
Year 2 field trips	Field trips to workshop Mgwalana, T12A and Mahlungulu, S50E, T35B	To collect data on participant's aspired landscapes	Ordinary community members, traditional leaders, ward councillors, farmers, teachers and nurses	Developed a chapter on aspired landscapes which we submitted in deliverable 7
Year 2 workshop	Workshop in Mahlungulu, S50E, T35B	Workshopped participants on entrepreneurial opportunities that exist in the value-chain of wattle harvesting	Ordinary community members, traditional leaders, ward councillors, farmers, official from DEA and local entrepreneurs trading in wattle	Shared information about how community members can beneficially participate in the wattle harvesting value chain. And we linked community members with critical officials from DEA and entrepreneurs that are already trading in wattle
Year 3 field trips	Field trips to Mgwalana, T12A	To organise participants for a workshop	Traditional leaders, ward councillor and project participants	We got a date set and venue for the workshop
Year 3 workshop	Workshop in	Workshopped participants on how to	Ordinary community members, traditional leaders,	Spread information of how to make commercial value of cattle in the village. And we initiated the process of

Date	Activity – Workshop/ Dialogues/ Meetings	Aim	Participants	Outcome
	Mgwalana, T12A	make use of the livestock market offered by Meat Naturally	ward councillors, farmers	inviting livestock auctions in the community
Year 4 field trips	Field trips to Matatiele	Livestock farmers from Mgwalana to eye-witness livestock auction	Three livestock farmers from Mgwalana, T12A	Some members of Mgwalana witnessed how livestock auction is run, after which they managed to tell their own village members of the benefits of selling livestock at the auctions.
Year 4 workshop	Workshop at Rhodes University with high-level stakeholders	Feedback on WfW prioritisation plan for Tsitsa River using a MCDA	DEA, WfW, Gamtoos Irrigation Board, Rhodes University researchers working in Tsitsa	Updated draft plan for clearing prioritisation based on criteria and their importance (weighting) relevant to the management and operational stakeholders

5.7 Final note on workshops and community engagement by the project

Some of the community related project findings that have implications for WfW and DEA projects in the catchment are:

- In contrast to provisioning and cultural services, regulatory and supporting services were not well understood by the communities;
- Some of the ecosystem elements were said to be providing ecosystem disservices;
- The two primary concerns that the local people aspire to see improved in their natural environment are water sources and grasslands;
- Community members are very keen to participate in processes of wattle harvesting as entrepreneurs but do not know how to do so. There is need to support them, especially to help them register companies.

The project exposed the villages in which we worked to a number of opportunities that support livelihoods and at the same time assist with grassland management, including

- Entrepreneurs that harvest and sell wattle to PG Bison and the possibility to supply wattle to these companies or become entrepreneurs themselves.

- Working for Forests, Working for Energy, Working for Electricity, WfW and Working for Ecosystems that benefit the community through jobs but also furniture for schools and caskets, and charcoal production.
- Meat Naturally auctioning, beef value-chain project and rangeland stewardship.
- Livestock farmers are keen to sell their livestock at auctions run by Meat Naturally, but there are some processes such as branding and organising that they need to be assisted with.
- The village cattle auctions that are being run by Meat Naturally offer a more lucrative market to subsistence livestock farmers, and hence should be supported.

Two general learnings that the group had was the need to build understanding and trust with the community through networking as a first step. Behavioural change took longer than we expected so sufficient time needs to be included in the project to interact with the communities. The business plan presented in Section 5.4.5 requires long-term engagement with the communities and might require a champion to take this forward. Such a champion could be an individual(s) in the Department of Social Development as a recommendation.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

This chapter provides a summary of the main findings and resulting conclusions arrived at during this project, together with our resultant recommendations for policy development and future research.

6.1 Ecosystem services as an over-arching framework

Approaches to ecosystem services have up to now been largely anthropocentric. This is potentially an environmentally unsound approach, and is something that needs to be brought to the attention of policy makers, particularly if one is arguing for the importance of an integrated approach to SES. This project took on the latter approach by bringing together scientific and social knowledge for research on rehabilitating grasslands after removal of invasive aliens.

The following three major recommendations are derived from our research that have implications for future research, as well as work conducted by different *Working for* programmes (such as WfW) and DEA projects in the catchment:

- In order for a RES framework to operate effectively, there needs to be a strong relationship between the resource and the products / services produced.
- In contrast to provisioning and cultural services, the regulatory and supporting services were not well understood by the communities. Thus, researchers and practitioners need to consider means and opportunities to improve the capacity of local people to respond to signals from the natural environment that are not immediately obvious or have direct impacts on the community, such as carbon sequestration, climate regulation, waste decomposition and detoxification.
- From both a research and a policy perspective, it is important to acknowledge the mutual complementarity of both more universal, scientifically-derived knowledge and more locally situated knowledge and values in ecological services related undertakings, including water services decision making. It is important that policies continue to be developed for the devolution of WRM to local level groupings. Thus, policy and decision-makers should consider implementing actions and policies that contribute towards RES practices at local level.

6.2 Water resource protection

The community engagement aspect of our project found that the two primary concerns that the local people aspire to see improved in their natural environment are water sources and grasslands. Communities indicated interest in grazing camps that can be used over winter and summer in order to prevent overgrazing. There was also support for improving the current soils, grasses, strengthening pasturing lands, and thinning as a strategy. These are all leveraging points for future interaction with and involvement of the communities in managing their land and water resources.

Improving rangeland productivity through grazing management is one possible way of improving LWP. An adaptive stocking density and appropriate herd composition strategy may positively influence vegetation ground cover, species composition and NPP, and thus improve water use. The results of our study showed that rangeland production does not depend on the tenure system as communal rangelands were as productive as commercial ones. This implies that many factors exist that determine the annual herbage production other than grazing. Therefore, there is a need for proper grazing management plans to be put in place to prevent excess water loss on communal rangelands.

6.3 Household water and food security

The link between good catchment and landscape management and household food security is very tenuous as there is seldom a clear link between compliance by a household and 'return for effort', or obvious advantages accrued by complying with landscape management. It is most often the poorer households that suffer as a result of non-compliance by other villagers. There are several explanations for this fractured relationship. The first is that those who comply easiest are usually more accessible to the community (they attend meetings, take an active role in the community, have a highly developed social conscience), whereas those who are not resident but have rights to grazing are less easy to access. They are often absent residents, with external income from cities and towns; however, they are viewed as important members who continue to provide remittances to permanent residents but are not involved in the catchment management discussions and enforcement. Another explanation is that poverty and the possibility of employment opportunity drives people to attend meetings and take on responsibility within committees. These individuals are often poorly resourced and are less able to cope with the power imbalances that arise when dealing with better-resourced, or 'richer' non-compliant community members. The voices of these individuals need to be brought to the fore in research projects whenever possible.

In the mixed farming system that we studied, livestock production is a key attribute of household food and livelihood security. By identifying the various production domains, and assessing their relative contribution to grass production, we are now able to recommend where appropriate interventions should be applied to achieve enhance livestock production. For example, in the abandoned cultivated lands, there should be an active programme to avoid further invasion by black and silver wattle. In this domain, there should also be an active policy to assist with soil remediation (e.g. increasing the pH by addition of lime), and the planting of appropriate fodder grasses that will enhance livestock production during the dry season. In addition, the introduction of effective herding in the use of the unimproved grasslands, where livestock are taken to new, un-utilised areas on a daily basis, will enhance livestock performance. This, when combined with improved market access, will greatly enhance the household income from both sheep and cattle, which are the main livestock-based livelihood strategies.

6.4 Catchment governance

The aerial maps used during the first workshop were effective in understanding the dynamics of the area, and in generating discussion about ideas on intervention and rehabilitation. We recommend use of these maps in future interaction with communities to allow them to gain better understanding of their resources and for discussing ways for managing these resources cooperatively.

We recommend that rehabilitation by agencies external to the communities ought to be conceived in terms of some of the social concerns facing communities instead of simply for improving soils or planting grasses. Wattle is important as a resource in some areas e.g. for fencing, construction, as a fuel source. Protecting and improving grazing seemed to be the most important aspect of rehabilitating lands after the removal of wattle.

This study results revealed huge variations in selected soil abiotic factors across environmental gradient in response to the invasion of *A. mearnsii*. Both the site and interactive effects of site and invasion status contributed significantly to variations in soil variables. Hence, any rangeland management intervention in complex SES should be informed by an appreciation of local soil physico-chemical properties. Linked to this, the clearing and liming trial experiment showed that grasses can return in significant biomass when grazing is excluded for as short a period as six months. This supports the idea of resting being an important part of grassland management.

6.5 Recommendations for future research

There are potential commercial partnerships which need to be embraced and supported given there are strong connections already taking place with PG Bison for some villages. Communities also indicated interest in removing wattle and having pine as a communal resource for homestead use in construction, as well as a revenue generation stream through sale to PG Bison. We therefore, suggest future research to investigate how these connections can be forged between communities and industry.

The findings from the ecosystems services surveys suggest that future research needs to interrogate means and opportunities to improve the capacity of local people to understand the importance of regulatory and supporting services. As noted above, researchers and policy makers would need to investigate implementation of a RES programme at local level to promote coherent and sustainable catchment management by the communities.

It is important that participatory and community-enabling research methodologies be developed at the local level, to enable local people more effectively to comprehend and negotiate the central issues relating to their natural environment and to ecosystem services, and to deal with policy makers in this regard. This calls for long-term engagement with local communities on the part of researchers, and potential development agents from universities, research institutions and non-governmental organisations (NGOs), etc. Therefore, funding agencies and researchers need to consider ways that such long-term projects that enable communities can be sustained.

Relationships with the commercial beef and wool industries need to be further developed and cultivated. The wool marketing frameworks have already been established, with National Wool Growers Association (NWGA) and the various wool buyers (Cape Wool, BKB) already well represented in these communities. However, there was less evidence of successful beef marketing options, and the project encouraged the cattle farmers to organise regular auctions with Beef Naturally and to consider joining the Free-Range Beef Project of the DAFF-ARC-Cradock Abattoirs consortium.

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Appendix 1 CAPACITY BUILDING REPORT

Table A1.1 Project impact table

Year of Graduation	Student Name and Surname	University	Degree	Race	Gender
2016	Perpetua Okoye	Stellenbosch University	MSc	Black African	Female
2017	Christopher Scorer	Rhodes University	Honours	White	Male
2017	Onalenna Gwate	Rhodes University	PhD	Black African	Male
2017	Liezl Mari Vermeulen	Stellenbosch University	Honours	White	Female

Currently registered					
2018	Thantaswa Zondani	Rhodes University	Honours (part-time)	Black South African	Female
2018	Bukho Gusha	Rhodes University	PhD	Black South African	Female
2018	Liezl Mari Vermeulen	Stellenbosch University	MSc (partially funded)	White	Female

A1.1 Student contribution to project aim

The four aims of the project were:

Aim 1: To parameterize, evaluate and modify suitable models for ET, LWP and NPP estimates for IAPs and grasslands.

Aim 2: To explore and compare ET, LWP and NPP in three catchments with contrasting land tenure systems, comprising diverse biomass and condition states for grassland and IAPs.

Aim 3: To apply the selected models for predicting ET, LWP and NPP to these catchments.

Aim 4: To examine the possibility of using a RES system in rural rangelands as a possible solution to degradation and water issues (quantity and quality).

Dr Onalenna Gwate's thesis focusing on ET and NPP contributed to Aims 1-3.

Ms Gusha's PhD research on LWP including interaction with communities contributed to all project aims.

Ms Okoye's MSc thesis on land cover change provided information to Aims 2 and 3.

Mr Scorer's Honours project on looking at historical pattern of wattle spread helped achieve Aim 1.

Ms Vermeulen's Honours project generated a smartphone product for grazing capacity which contributes to Aims 1-3, and also Aim 4 by providing an interface for communities to use.

Finally, Ms Zondani's ongoing Honours project is taking forward Ms Gusha's work on LWP and looking at where livestock graze using GPS collars and thus it contributes to all four aims.

A1.2 Thesis abstracts

The abstract for Ms Perpetua Okoye's MSc thesis is as follows:

Rehabilitating grassland, a threatened biome, requires a comprehensive management approach that integrates the environmental, economic and social matters in sustaining this system. In the Eastern Cape of South Africa, three Quaternary catchments (QCs) (T35B, T12A & S50E) have been severely invaded by IAPs as well as altered by agrarian intensification and human development. WfW Alien Plant Clearing Programme have been clearing IAPs in these catchments for the past twelve years. The current research aimed at establishing various degradation gradients occurring in the QCs. This was done by conducting land cover classification and change analysis over time, evaluating soil quality and assessing the success of the WfW programme by quantifying the net primary production (NPP) and evapotranspiration (ET) trends on the cleared areas. A novel management scheme for decision makers, driver-pressure-state-impact-response (DPSIR) framework, was therefore suggested for managing these QCs sustainably.

The soil analysis showed that phosphorus (P) levels are significantly different ($P<0.05$) between invaded, cleared and natural sites. High nitrogen (N) and pH were associated with *Acacia* proliferation in acidic soils. Object based image analysis (GEOBIA) was used for the land use land cover (LULC) classification using Landsat 8 OLI & TIRS imagery. LULC change analyses were carried out on two reference bases [National land cover (NLC) 2000 & Edited NLC (ENLC) 2000]. Land cover change analysis was facilitated by using a framework introducing labels to describe land cover change. Annual MODIS ET (MOD16)/NPP (MOD17) data were used to evaluate the rehabilitation progress in T12A using WfW clearing data. A DPSIR management framework, structuring the sustainable indicators at the QCs in a logical manner, was developed for decision and policy makers for dealing with management issues related to land use, water resources and soil quality management.

The present research recommends that additional soil samples need to be collected for validation of soil nutrients status. Medium resolution Landsat imagery used for the LULC mapping provided accuracies of greater than 80%, but could not differentiate between invasive and indigenous trees. Hyperspectral or higher resolution imagery should be explored for mapping and delineating IAPs. Using coarse resolution MODIS products to model ET/NPP did not provide adequate detail of the cleared patches to describe the actual status of WfW clearings and their rehabilitation progress.

The abstract for Mr Chris Scorer's Honours thesis is as follows:

IAPs pose a threat to ecosystem integrity in many parts of the world. One such example - *Acacia mearnsii,* was introduced to South Africa in middle to late 1800s for its provisioning and economic use. In 1995 the South African government began the WfW programme which focused primarily on providing poverty relief to poor and disadvantaged people in South Africa by employing them to clear areas of alien vegetation from water courses and river catchments. Although the WfW programme has created and continues to create employment, the effectiveness of the programme in clearing and keeping clear previously infested areas is under review. This study establishes the magnitude and direction of spread of *Acacia mearnsii* in the T12A catchment within the Eastern Cape Province of South Africa. From initial plantings prior to 1958, wattle has spread more extensively into disturbed (i.e. over-grazed) or abandoned cultivated land, than into un-disturbed natural grassland. Biomass estimates were also conducted at a number of preselected sites in order to establish the biomass of *Acacia mearnsii* stands of different ages. Total above-ground standing biomass varied from 170 $ton.ha^{-1}$ to over 550 $ton.ha^{-1}$. With a mean of 295 $ton.ha^{-1}$ from 32 plots. The model of *Acacia mearnsii* annual growth (y = 9.573x + 24.892) indicates it accumulates biomass at a rate of nearly 10 $ton.ha^{-1}.annum^{-1}$. Lastly, an assessment of the two main clearing strategies of WfW was conducted to gain some insight into how much of the infested area T12A is suitable for manual clearing or alternatively biocontrol methods.

The abstract for Ms Liezl Mari Vermeulen's Honours thesis is as follows:

IAPs have a detrimental effect on grassland land use productivity, both prior and post eradication, and lead to the degradation of grazing capacity. Current traditional geoprocessing and remote sensing approaches have their limitations in that they require highly specialized and expensive software, computers and training. This limits the usability of such approaches by non-expert users in remote areas with limited technology, funds and training. A gap can thus be identified, as there is no effective way to determine land use productivity in the field using limited technology. The aim of this research is to address this gap by developing a mobile application that estimates land use productivity in the field using Google Earth Engine.

Three water catchments, located in the Eastern Cape Province, South Africa, was selected as the area of interest. The study area is relatively rural and consists of majority grassland land cover, with the dominant land use being subsistence livestock farming. Both Landsat 8 and MODIS imagery was used, allowing a comparison of results obtained using high spatial (Landsat 8), as well as high temporal (MODIS) resolution imagery. Additional data included in situ LAI field measurements.

The selected satellite imagery and field measurements were used to develop a land use productivity model for grasslands with different levels of alien plant invasion. The model produced two main products: grass cover percentage (for estimating different levels of IAP invasion) as well as grazing capacity (to determine productivity of the grassland). This model was implemented using the geoprocessing cloud platform Google Earth Engine, addressing the software and hardware limitations of traditional, desktop-based remote sensing approaches. Hybrid mobile application technologies, in combination with Google App Engine, Google Cloud Endpoints Frameworks and Google Earth Engine, was then used to package the land use productivity model as a mobile application. The resulting hybrid mobile application was evaluated on both accuracy and efficiency. Accuracy was evaluated based on a comparative assessment between the various intermediate and final model products and MODIS data products, as well as reference grazing capacity maps. Efficiency was evaluated based on user feedback via questionnaires to determine the usability and user-friendliness of the application.

The research results suggest that, when estimating productivity of unstable and temporally variable ecosystems such as grasslands, a shorter temporal resolution (MODIS) is more relevant than a finer spatial resolution (Landsat 8). Landsat 8 provided overestimated grazing capacity output, thus characterising the area of interest with worse grazing conditions than expected. MODIS, however, consistently provided more accurate intermediate and final model products, with a final RMSE of 0.75 ha per LSU compared to MODIS' 1.91 ha per LSU.

With respect to efficiency, the application proved to be both user-friendly and usable based on user feedback, with accessibility as a characteristic to improve on.

The aim of the research was achieved, as mobile application was developed that allowed accurate and efficient estimation of land use productivity in the field. The use of geoprocessing cloud platforms and mobile development technologies thus prove valuable tools in addressing the limitations of traditional, desktop-based approaches when determining productivity of unstable, temporally variable ecosystems. The study consequently contributes to determining the effects of IAP invasion of grassland productivity, both prior and post eradication, as well in improving agricultural monitoring and management systems of local farmers in rangelands and grasslands. Recommendations for future research include collecting more field measurements for the calibration and validation of the model to increase application accuracy. Further research on mobile application development platforms must also be conducted to allow improving the communication of the various components of the application, as well as to ensure a more usable and user-friendly application.

The abstract for Mr Onalenna Gwate's PhD thesis is as follows:

It is imperative to understand the strong coupling between the carbon capture process and water use to sustainably manage rangelands. Woody encroachment is undermining rangelands grass production. Evapotranspiration (ET) highlights the links between ecosystem carbon capture process and water use. It forms the biggest flux of the hydrological cycle after precipitation yet it is not well understood. The Grassland and the Albany Thicket (AT) biomes in the Eastern Cape, South Africa, provide an interesting space to study the dynamics in rangelands biomass production and the associated water use. Therefore, the main purpose of this study was to contribute towards management of rangelands by understanding the dynamics in rangeland grass production and water use. To achieve this aim, the impact of *Acacia mearnsii*, an invasive alien plant, on soil chemical properties and rangelands grass production was investigated. This was achieved by analysing the biophysical attributes of A. *mearnsii* as they related to grass production. Secondly, selected soil variables that could be used as a prognosis for landscape recovery or deterioration were evaluated. In addition, above-ground grass biomass was measured in areas cleared of *A. mearnsii* and regression equations were prepared to help model above-ground grass biomass in areas cleared of *A. mearnsii*. The thesis also explored dynamics in water vapour and energy fluxes in these two biomes using an eddy covariance system. Consequently, water vapour and energy fluxes were evaluated in order to understand landscape water use and energy partitioning in the landscape. The study also tested the application of Penman-Monteith equation based algorithms for estimating ET with micrometeorological techniques used for validation. Pursuant to this, the PML and PMP equations were applied. In addition, some effort was devoted to improving the estimates of ET from the PMP by incorporating a direct soil evaporation component. Finally, the influence of local changes in catchment characteristics on ET was explored through the application of a variant of the Budyko framework and investigating dynamics in the evaporative index as well as applying tests for trends and shifts on ET and rainfall data to detect changes in mean quaternary catchment rainfall and ET. Results revealed that A. *mearnsii* affected soil chemical properties and impaired grass production in rangelands. Hence, thinning of canopies provided an optimal solution for enhanced landscape water use to sequestrate carbon, provide shade, grazing, and also wood fuel. It was also shown that across sites, ET was water-limited since differences between reference ET and actual ET were large. ET was largely sensitive to vapour pressure deficit and surface conductance than to net radiation, indicating that the canopies were strongly coupled with the boundary layer. Rangeland ET was successfully simulated and evaporation from the soil was the dominant flux, hence there is scope for reducing the so-called 'unproductive' water use. Further, it was shown that the PML was better able to simulate ET

compared to the PMP model as revealed by different model evaluation metrics such as the RMSE, absolute mean square error and the root mean square observations standard deviation ratio. The incorporation of a soil evaporation component in the PMP model improved estimates of ET as revealed by the RMSE. The results also indicated that both the catchment parameter (w) and the evaporative index were important in highlighting the impacts of land cover change on ET. It was also shown that, despite changes in the local environment such as catchment characteristics, global forces also affected ET at a local scale. Overall, the study demonstrated that combining remote sensing and ground-based observations was important to better understand rangeland grass production and water use dynamics.

The abstract for Ms Bukho Gusha's PhD thesis is as follows:

Communal rangelands in South Africa mainly occur in the former homelands. The former homelands constitute 13% of the land surface area and support a quarter of the country's human population with a wide range of goods and services, among them, grazing for livestock, mostly reared on communal rangelands. These rangelands are degraded and cannot sustain maximum livestock production because of poor species composition and low standing biomass, but little research has been conducted on livestock production at household level (where all livestock goods and services are valued). This provides an opportunity to conduct a study describing livestock water productivity in the north of the Eastern Cape, where livestock production is a primary source of livelihood for rural communities from which many households generate cash but where different practices and factors undermine high livestock production.

Many studies have focused on understanding the water productivity of a natural rangeland system for commercially oriented crop-livestock systems, but the aim of this study is to contribute towards improving rural livelihoods from livestock in the sub-humid rangelands of the north Eastern Cape. Here, unimproved native grasslands are the major source of feed for livestock and people do not have herders to take livestock to the most productive parts of the rangelands.

Households were surveyed using a questionnaire on livestock household contribution, socio-economic characteristics of the household, livestock holdings and livestock production strategies. Rangeland productivity was measured in the field. Experimental animals for livestock grazing distribution were identified and fitted with Global Positioning Systems (GPS) collars to identify the seasonal grazing areas. These activities shed light on the biophysical attributes of the ecosystem and livestock production in a communal rangeland system.

Because continuous grazing in the rangelands of the north Eastern Cape reduces the standing biomass, there is no obvious aboveground biomass to provide a visual perspective of production nor is it possible to determine production without excluding the livestock. Thus, four parallel lines of evidence were employed to measure rangeland productivity: line intercept, grazing exclosures, net photosynthesis from earth observation and disc pasture meter. Earth observation products were used to derive the amount of water used by the landscape to produce this forage (i.e. evapotranspiration or ET) and these measurements of net primary production and landscape water use were used in preparing a value of livestock water productivity (LWP) for this farming system.

People in the study area lack local knowledge of technical efficiencies in the large stock sector at household level. The study used stochastic frontier analysis to assess livestock production and followed with a household survey to collect information on socio-economic characteristics and information on livestock practices. Productivity and inefficiency variables that increase livestock production or increase technical difficulties were identified. The focus on livestock has mostly been on the direct value of livestock to owners with a poor understanding of their value to non-livestock owners, where cultural activities, such as livestock slaughtering, were documented as the only source of protein for non-livestock owners. However, the value that is available to non-livestock owners has not been quantified. This study assessed livestock-based livelihoods of communal people to improve their livelihoods through a household survey looking at the contribution of livestock to both livestock and non-livestock owners. Earlier work on LWP has focused on systems where animals were on 'fed, cut and carry' and irrigated systems. However, there is a need to describe LWP in a natural grazing system and this study set out to achieve this for these communal rangelands through a household survey that determined the value of livestock goods and services given the amount of water used (ET). Lastly, livestock grazing distribution across the landscape was assessed, using GPS collars that recorded livestock behaviour every five minutes during the daylight. This approach was necessary because livestock grazing patterns in these communal rangelands is poorly controlled by people, and animals are largely free-ranging, grazing selectively, based on their own preferences, which leads to localised overgrazing. This part of the study was achieved through experimental livestock collaring and weighing (both sheep and goats) for the wet and dry seasons. The results on livestock grazing distribution were analysed using the R package, T-LoCoH.

The major finding of this study was that communal rangelands of the north Eastern Cape can improve rural livelihoods from livestock if proper interventions for both livestock and rangeland production and productivity can be implemented. One of these interventions is fencing as it was found that exclosures that were fenced during the study yielded high aboveground productivity comparable to that achieved in commercial rangelands, yielding 220 g DM m-2 yr-1. Surveys using the calibrated disc pasture meter showed the need for proper rotation and resting of the rangeland. Net photosynthesis of 880.7 g C m-2 yr-1 for unimproved grassland in good condition was comparable to commercial rangelands in the region. Using the line intercept, vegetation cover was found to be a good predictor of aboveground standing biomass; thus a positive relationship was revealed. Lastly, annual ET of 270 mm yr-1 was calculated using the Penman Monteith Palmer (PMP) equation, while 379 mm yr-1 was extracted from the MOD16 product, suggesting that PMP ET may not be accurate in these grassland systems due to the slow response of MODIS Leaf Area Index (LAI).

The average household technical efficiency (TE) score was found to be 0.79 on the study sites, indicating the potential for households to improve outputs from livestock. A range of household categories were identified, based on gender and an index of wealth, and households with lower and higher TE were identified. This analysis revealed that productivity variables such as holding higher livestock numbers and providing additional feed achieved high livestock outputs, suggesting high livestock productivity. However, in terms of inefficiency variables, gender (female-headed households), dwelling type (an index of homestead wealth), kraaling livestock at night and herding livestock during the day were found to improve technical efficiency. It was revealed in this study that households keep livestock to derive different goods and services including offtake, manure, milk, wool and services such as traction. The non-livestock owning households were reported to also benefit from the abovementioned goods and services in the study site and that the value of their contribution could be quantified, thus contributing significantly to rural livelihoods.

The study showed that LWP was comparable with other studies such as those conducted in Ethiopia. This study compared its results with the studies conducted outside South Africa as there were limited comparable South African studies available; however, this does not necessarily mean we can use the same model as the value of livestock outputs varies based on the preferred outputs. This study developed an LWP model for the natural rangeland system. The LWP values measured in USD were divided into three different categories based on the wealth index, such as better-off, middle wealth and poor households.

Lastly, this study showed that livestock (both cattle and sheep) spend a high proportion of their grazing day, during both the wet and dry seasons, in a small physical area, immediately around the homesteads. These are areas where the active green growth occurs throughout the year, suggesting the need for livestock herders to move livestock around the landscape for more effective landscape use. Herding has the potential to improve landscape use and the ability of a household to attain best outputs from livestock. Positive daily weight gains were reported in collared livestock during the wet season. However, both sheep and cattle lost weight during the dry season.

This study recommends interventions such as labour for herding, and other animal husbandry-related activities including milking, handling, and vaccinating animals. Market opportunities for communal rangeland livestock should be facilitated by informing livestock owners about livestock market specifications to improve their livelihoods. Lastly, proper grazing management planning, such as fencing, which enables rotational grazing, and herding which moves animals to the most productive parts of the rangeland, should be implemented so that rangelands can be rested for plant growth, vigour, and improved aboveground net primary productivity. Based on the recommendations made in this study, a research development approach is necessary which prioritises female empowerment in agriculture and poor farmers as female-headed households were reported by this study to be more technically efficient. This would be done by conducting another household survey where two different groups of households would be identified. Interventions along the lines of the recommendations of this study would be implemented in one group, and the other group would serve as a control where no interventions were applied. Livestock production would be measured after a year. The household questionnaires would be improved to include more detailed information on the livestock products produced and specific seasons where sales were conducted, and both livestock herders and livestock owners would be interviewed.

Table A1.2 Conferences/Presentations made by research team

Date	Presenter	Conference	Title
June 2014	Perpetua Okoye	SA Geographers Conference, East London, South Africa	No presentation; course on Introduction to Earth Observation
Sept 2014	Onalenna Gwate	Arid Zone Ecology - Thicket Fusion Forum, Grahamstown, South Africa	Modelling evapotranspiration, livestock water productivity and water use efficiency in three rural catchments of the Eastern Cape using Earth observation techniques
Sept 2014	Sukhmani Mantel	Arid Zone Ecology - Thicket Fusion Forum, Grahamstown, South Africa	Estimating evapotranspiration following clearing of invasive aliens: effects of patchy landscapes
July 2015	Bukho Gusha	Annual Congress of the Grassland Society of Southern Africa (GSSA) Congress, Pietermaritzburg, South Africa	Assessing the concept: Livestock water productivity in the rehabilitation and management of rangelands after the clearing of invasive alien plants
July 2015	Sukhmani Mantel	Annual Congress of the Grassland Society of Southern Africa (GSSA) Congress, Pietermaritzburg, South Africa	Impacts of high density of small farm dams on evapotranspiration and catchment water balance
July 2015	Onalenna Gwate	Annual Congress of the Grassland Society of Southern Africa (GSSA) Congress, Pietermaritzburg, South Africa	Influence of *Acacia mearnsii* (black wattle) on rangeland production in semi-arid South African grasslands: implications for rangeland rehabilitation
July 2016	Onalenna Gwate	International Rangeland Conference, Saskatoon, Canada	Exploring dynamics of evapotranspiration in a semi-arid grassland of South Africa
Sept 2016	Onalenna Gwate	SPIE Remote Sensing Conference, Edinburgh, Scotland	Modelling evapotranspiration using the modified Penman-Monteith equation and MODIS data over a subtropical thicket in South Africa Measuring evapotranspiration using an eddy covariance system over a subtropical thicket of the Eastern Cape, South Africa
March 2016	Adam Perry	76th Annual Meeting of the Society for Applied Anthropology, Vancouver, Canada	'Emva kwe dywabusi' or 'Beyond the removal of wattle, what next'? Aerial mapping and community development as participatory learning in an Eastern Cape context, South Africa

Date	Presenter	Conference	Title
July 2016	Bukho Gusha	Annual Congress of the Grassland Society of Southern Africa (GSSA) Congress, George, South Africa	Livestock ownership and management: A case of Mgwalana village, Eastern Cape, South Africa
June 2017	Anthony Palmer	Thicket Forum, Eastern Cape, South Africa	Challenges to measuring carbon fluxes in the Albany Thicket
Sept 2016	Zahn Münch	Society of South African Geographers (SSAG), South Africa	Evaluating temporal landscape change using intensity analysis and trend analysis
Oct 2016	Zahn Münch	Workshop for Early Careers Researchers on Ecosystems Services for Water and Food, Stellenbosch, South Africa	A framework for assessing ecosystem services in preparation for reward for ecosystem services (RES) system
July 2017	Bukho Gusha	Annual Congress of the Grassland Society of Southern Africa (GSSA) Congress, South Africa	Performance of livestock production in the north Eastern Cape communal areas: A stochastic frontier analysis
Oct 2017	Bukho Gusha	Department of Environmental Science Research Forum, Rhodes University, South Africa	Performance of livestock production in the north Eastern Cape communal areas: a stochastic frontier analysis
Sept 2017	Liezl Mari Vermeulen	Geo-Information Society of South Africa (GISSA), South Africa	A novel approach to deriving land use productivity using Google Earth Engine
Oct 2017	Liezl Mari Vermeulen	South Africa National Space Agency (SANSA) Bursary Holders Conference, South Africa	A novel approach to deriving land use productivity using Google Earth Engine
Sept 2017	Zahn Münch	Workshop for Early Careers Researchers on Ecosystems Services for Water and Food, Stellenbosch, South Africa	A framework for assessing ecosystem services in preparation for reward for ecosystem services (RES) system
Oct 2017	Zahn Münch	Society of South African Geographers (SSAG), South Africa	Evaluating temporal landscape change using intensity analysis and trend analysis
Sept 2017	Lesley Gibson	International Symposium on Soil- and Water Bio-engineering in a Changing Climate, Glasgow	Land cover change prediction in South African grasslands towards determining the catchment carbon-water-surface energy flux nexus
July 2018	Thantaswa Zondani	Annual Congress of the Grassland Society of Southern Africa (GSSA) Congress, South Africa	Assessing livestock grazing distribution on communal rangelands of Cata and Guquka, Eastern Cape, South Africa

Date	Presenter	Conference	Title
Apr 2018	Liezl Mari Vermeulen	The 7th Digital Earth Summit 2018, DES-2018, Morocco (winner of ISDE travel award for young scientists)	A novel approach to deriving land use productivity using Google Earth Engine
July 2018	Sukhmani Mantel	Annual Congress of the Grassland Society of Southern Africa (GSSA) Congress, South Africa	Towards a Strategy for Management of Invasive Aliens for Tsitsa River Catchment: WfW Prioritisation Clearing Plan
July 2018	Anthony Palmer	Annual Congress of the Grassland Society of Southern Africa (GSSA) Congress, South Africa	Measuring carbon and water fluxes in the Albany Thicket, Eastern Cape

A1.3 Scientific papers/ publications

A1.3.1 Peer-reviewed scientific publications

- Gwate, O., Mantel, S., Finca, A., Gibson, L., Munch, Z. and Palmer, A. (2016) Exploring the invasion of rangelands by *Acacia mearnsii* (black wattle): biophysical characteristics and management implications. *African Journal of Range & Forage Science*, 33(4), pp.265-273.
- Münch, Z., Okoye, P., Gibson, L., Mantel, S. and Palmer, A. (2017) Characterizing Degradation Gradients through Land Cover Change Analysis in Rural Eastern Cape, South Africa. *Geosciences*, 7(1), p.1-5. doi:10.3390/geosciences7010007.
- Palmer, A., Finca, A., Mantel, S., Gwate, O., Münch, Z. and Gibson, L. (2017) Determining fPAR and leaf area index of several land cover classes in the Pot River and Tsitsa River catchments of the Eastern Cape, South Africa. *African Journal of Range & Forage Science*, 34(1), pp.33-37. DOI: 10.2989/10220119.2017.1306582
- Gibson, L., Münch, Z., Palmer, A. and Mantel, S. (2017) GIS approach to land cover change prediction in South African grasslands towards determining the catchment carbon-water-surface energy flux nexus. *Procedia Environmental Science, Engineering and Management*, 4(4), pp.219-226.
- Gibson, L., Münch, Z., Palmer, A. and Mantel, S. (2018) Future land cover change scenarios in South African grasslands – implications of altered biophysical drivers on land management. *Heliyon*, 4(7), p.e00693. https://doi.org/10.1016/j.heliyon.2018.e00693.
- Gwate, O., Mantel, S., Gibson, L., Munch, Z. and Palmer, A. (2018c) Exploring dynamics of evapotranspiration in selected land cover classes in a sub-humid grassland: A case study in quaternary catchment S50E, South Africa. *Journal of Arid Environments*, 157, pp.66-76.

- Gwate, O., Mantel, S., Palmer, A., Gibson, L. and Munch, Z. (2018a) Measuring and modelling evapotranspiration in a South African grassland: Comparison of two improved Penman-Monteith formulations. *Water SA*, 44(3), pp.482-494.
- Gwate, O., Mantel, S., Palmer, A. and Gibson, L. (2018b) Biophysical controls of water vapour and energy fluxes: Towards the development of biome scale predictive models of evapotranspiration in the Albany Thicket, South Africa. *Ecohydrology*, p.e2031.
- Scorer, C., Mantel, S. and Palmer, A. (2018) Do abandoned farmlands promote spread of invasive alien plants? Change detection analysis of black wattle in montane grasslands of the Eastern Cape. *South African Geographical Journal*, https://doi.org/10.1080/03736245.2018.1541018.

A1.3.2 Peer-reviewed conference proceedings

- Gwate, O., Mantel, S., Palmer, A. and Gibson, L. (2016). Modelling evapotranspiration using the modified Penman-Monteith equation and MODIS data over the Albany Thicket in South Africa. *Remote Sensing for Agriculture, Ecosystems, and Hydrology XVIII*, doi:10.1117/12.2245439.
- Gwate, O., Mantel, S., Palmer, A. and Gibson, L. (2016). Measuring evapotranspiration using an eddy covariance system over the Albany Thicket of the Eastern Cape, South Africa. *Remote Sensing for Agriculture, Ecosystems, and Hydrology XVIII*, doi:10.1117/12.2245426.
- Gusha, B., Palmer, A.R. and Villano, R.A. (2018). "Performance of livestock production in north Eastern Cape communal areas: a stochastic frontier analysis," 2018 Conference, July 28-August 2, 2018, Vancouver, British Columbia, International Association of Agricultural Economists.

A1.4 Additional funding support received

NRF Indigenous Knowledge System funding for R761,489 (2017-2019) including bursaries worth R305,000. Title: *IKS to enhance rewards for ecosystem services in rangelands infested with invasive alien plants*. Mr Chenai Murata is registered as a PhD candidate under the supervision of Dr Palmer and Prof. Gladman.

NRF National Equipment Programme (2014) was used to purchase two Eddy Covariance systems and one LAS which were used to collect data for Mr Gwate’s PhD thesis.

Appendix 2 DESCRIPTION OF SOME OF THE RITUALS AND BELIEFS OF THE RESPONDENTS

The following is a description of the respondents' rituals and beliefs that are linked directly or indirectly to the natural environment, with many of the rituals taking place in the natural environment (related to Section 5.2).

Intonjane (Initiation for girls): This is a ritual done for young girls to introduce and prepare them for a wedding. They are taught about the expectations of being a wife and a mother. These teachings are done by older women who share their experiences with the young girls. The girls are kept in seclusion for some time (3 weeks) in land far away from the households. Female genital mutilation was practiced in secret but South African law has outlawed it. As a result, most tribes have ceased this practice.
Ulwaluko (initiation for boys): This is a ritual done for young boys to introduce them to manhood. They are kept at a secluded site, far from the village. They are taught responsibilities of a man and how to carry themselves as men. The details to the surgical part and further knowledge are kept secret. Circumcision is believed to prevent transmission of diseases that may be stored in the foreskin during sexual intercourse.
Artefacts: These are of aesthetic and ornamental value hence these are the works of indigenous art. Things made of mud (pots, bowls, plates, cups etc.), stone (paintings, arts), grass (mats, brooms, and paintings), animal skin and hides (mats, blankets, coats and shoes, leather).
Caves: Historical places where comrades used to meet for their meeting during the apartheid era and also others are sacred places people go to affirm to their roots and also have contact with their ancestors.
Worshiping of mother nature: This involves spiritual contact with ancestors in the form of worshiping mountains, rivers and also nature generally. People from the community go to the top of the mountain, slaughter a certain bird species and this will eventually cause rain. This is mostly performed during periods of prolonged drought.
Intlombe: This is a ceremony done for witch doctors when they acknowledge the spirits that give guidance to them and the spirits to which they account to and receive mandate from. This involves the spilling of blood and that is animal blood usually chicken.
Recreational activities: Soccer is the most common and popular sport played in both villages hence they use some parts of the land as soccer fields.
Imbeleko: Welcoming of a new-born to the family and introducing it to the family and ancestors in the form of a ritual of slaughtering a goat and using parts of the goat skin to make a bracelet or waist rope to protect the child from evil spirits and also they are left until they fall of on their own. They can also be replaced depending on the culture of the household.
Utsiki: Traditional wedding done for the bride to welcome her in the new family. She sits in the corner of the room and bows down so that the elders can address her as to what they expect from her and how she should carry herself as the wife. This involves slaughtering of goat and smearing blood from and bile on certain parts of her body so that she is protected from evil.

Uvulo lomzi: Introduction of house to ancestors so that they recognise it among the rest and protect it from evil spirits. There is also slaughtering of an animal because blood has to be spelt in the process. The type of animal depends on the family's culture and customs.
Visitation of home by a snake (*Majola*) clan name. This snake is usually seen when there is a new-born in the family so it comes to welcome the baby, when there is a celebration, ritual performed or even funeral. The family with the clan acknowledge its presence and the family shows appreciation by putting an egg and a silver coin in the centre of the room.
Presence of an owl in the home means bad luck (Omen) and also the monkeys hand is used to curse the family. Those in possession of the monkey's hand are believed to practice witchcraft. Ownership of tortoise means protection of home from any harm and evil.
Animal skins are used to make traditional medicine and herbs like meerkat skin which is used to make medicine. Bees come as ancestors and usually visit the family that is related to them by clan and African beer is used to chase them back to where they come from. From time to time they visit.
Certain plant species within the landscape are used to protect and chase away evil spirits. These remain a secret among the traditional healers.
Koisan language on caves, rocks and forests to remind people of their rich history and also a way to affirm to roots maybe bring them back to basics. Reminding people about where they come from, their culture, customs and heritage.

Appendix 3 BIODIVERSITY COMPONENTS RECOGNISED BY THE RESPONDENTS TO SUPPORT BOTH CULTURAL AND SUPPORTING SERVICES (SECTION 5.2)

Given name of animal	Description of the role that these species are perceived to play in both cultural and supporting services.
Caracal or lynx	This animal is known in the villages and is perceived to be dangerous as it preys on small stock. It may attack them as well that is why precaution is taken when going into the mountain or forest.
Porcupine	This is also a type of animal known to be present and in some houses you would find their feathers used as decoration. It is not known to attack but people are aware of the dangers associated with their feathers.
Civet cat	This is a wild animal known to be present but have been seen by the few people hence it walks far from the households. It is a carnivore so people are on the lookout when going to the forest and mountain hence it may attack.
Spotted hyena	These animals are very rare to find within the village and when seen they always a cackle of hyenas. They are harmful to small stock usually when the herder is absent or unguarded stock. Very few people have seen them and is believed to remain within their natural habitat. They may attack human beings and respondents are aware of the dangers associated with these animals. *It is unlikely that this species has been seen by this respondent as they have been absent from this area for over 100 years.
Common reedbuck	Few respondents hunt the animal and eat them.
Chuck*	This is a wild animal species known to the village and there is little to no fear for the animal. It is commonly known as being a lazy animal hence they also have a Xhosa proverb; that it lost its tale because of laziness. *This is a rock hyrax or dassie.
Plateau birds	These are the beautiful, colourful and popular birds known to visit during Christmas. These come in different species and mean no harm to the people; people appreciate their presence and they also mean no harm to the birds.
Ravens	These are the black birds with white collar and the people are aware of their presence. *There were no further comments about the birds and people seem to live in harmony with them.
Hawk	This is a type of bird known to hunt and capture chicken and chicks from the ground and later on feeds on them.

Given name of animal	Description of the role that these species are perceived to play in both cultural and supporting services.
Leguaan	This is a reptile which belongs to the cold blooded animals and resembles a big lizard. This animal is believed to suckle on cow teats when they go to drink in the river and leaves the cows teats with rash.
Hem bird	This is a common wild bird, known by the respondents which means no harm to the people and people also mean no harm to the bird. *There were no further comments from the respondents.
Shepard birds	These are the birds that like to be near cattle especially when they feed, they are white in colour and are known to eat ticks from the skin coat of cattle.
Bucoruuus leadbeateri (Southern ground Hornbill)	*Respondents mentioned the presence these birds, but there was no further comment on their presence or usefulness of them.
Owl	Presence of an owl in homestead is known to bring bad luck, witch doctors use their feathers within their room to which they heal people.
Mole	This animal is believed to eat crops from vegetable gardens and damages the grass lawns with the burrowing of soil.
Earth worms	Respondents mentioned the presence these worms, but there was no further comment on their presence or usefulness.
Lizard	Respondents mentioned the presence of these lizards, they are also aware that they are not poisonous animals prefer to kill it when found inside the house and few fear it because it is a reptile.
Snakes	In both villages most of the time snakes are killed whenever seen and there is no form of knowledge as to which ones may be poisonous except for the one snake (Majola) known to visit people related with.
Rabbit	This animal is widely hunted in the village, some hunt and eat the meat, some hunt to use its skin as decoration and also hunt to kill it because it also eats the vegetables from the gardens.
Jackal	This animal is an enemy in both villages and is known to consume the internal organs of lamb. It is also known as very smart because it preys on a lamb; when hungry it will prey on another and will not finish up the lamb it initially fed on. When seen it is killed and is also the most hunted animal. Its skin is used to decorate the house either making a mat or as a sculpture on wall. It is very popular even within the houses hence it may be seen on kraals. Dogs bark at the animal, mostly to alert the people and it usually makes a distinct sound.
Vulture	These are the type of birds seen to eat dead animals from the villages.

Given name of animal	Description of the role that these species are perceived to play in both cultural and supporting services.
Locust	This is an insect very popular in gardens and is known to damage the leaf margins of the crops.
Tortoise	Traditionally the person owns one as a pet is known to be protected from evil spirit and from any harm. They also say this animal also eats from the garden but the damages caused are negligible hence it is perceived as a harmless animal.
small antelope	Hunted by very few and eaten also by very few. They are seen as no harm to the villages. *Respondents could not differentiate between the numerous different species of small antelope which occur in the region.
Polecat/zorilla/ lesser spotted genet	*Respondents mentioned the presence this cat, but there was no further comment on their usefulness besides from being dangerous and preys on small stock.
Meerkat or mongoose	Traditional medicine is made up of its skin and the details are kept as a secret among traditional healers. Preys on small stock and may attack human beings.
Fish	Very few people still go out fishing and those that are seen to are only in one of the villages (Mahlungulu). Small boys just fish for leisure when out in the field. There is little interest to fishing.
Wild spiders	Spiders are killed in the villages especially big black ones although there are house spiders in corners of the rooms and those are there; either because of ignorance or because they don't clean the house properly.
Frogs	The respondents were aware of the presence of frogs. A few respondents expressed fear of frogs, reporting that a poisonous liquid could cause skin inflammation and sores. They are usually killed when seen. This preferred method is by pouring salt on their skin. It is also believed that their presence could attract snakes.
Lice	These are usually seen in people's hair, under armpits or in pubic hairs and are an indication of lack of cleanliness to the individual. They also can be infested in a home also because of lack of cleanliness and proper hygiene. It is embarrassing and humiliating to have these around someone and may cause isolation from society.