# 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

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**ONALENNA GWATE** 

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#### ABSTRACT

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, aboveground grass biomass was measured in areas cleared of A. mearnsii and regression equations were prepared to help model aboveground grass biomass in areas cleared of A. mearnsi. 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 Penman-Monteith-Leuning (PML) and Penman-Monteith-Palmer (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 root mean square error, 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 root mean square error. 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.

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### **ABBREVIATIONS**

AGB	Aboveground biomass
ANPP	Aboveground net primary productivity
AT	Albany Thicket
AWS	Automatic weather station
CAM	Crassulacean Acid Metabolism
CDM	Clean development mechanism
CV	Coefficient of variation
DBH	Diametre at breast height
DPM	Disk pasture meter
EBR	Energy balance closure ratio
EC	Eddy covariance system
EGR	eZulu Game Reserve
IAPs	Invasive alien plants
IRGASON	Integrated CO <sub>2</sub> /H <sub>2</sub> O Open-Path Gas Analyzer and 3D Sonic
	Anemometer
IWRM	Integrated water resources management
LAI	Leaf area index
LAS	Large Aperture Scintillometer
MAE	Mean absolute error
MAR	Mean Annual Rainfall (mm)
MDV	Mean diurnal variations
MODIS	Moderate Resolution Imaging Spectroradiometer
MOST	Monin-Obukhov Similarity Theory
MSE	Mean square error
NBAR	Nadir Bidirectional Reflectance Distribution Function Adjusted
	Reflectance
NLC	National Land Cover
NDVI	Normalised difference vegetation index
PBIAS	Percent bias
PCA	Principal omponents analysis
PM	Penman-Monteith
PML	Penman-Monteith-Leuning equation
PMP	Penman-Monteith-Palmer equation
REALU	Reducing emissions from all land uses

- RMSE Root mean square error RSR Root mean square error observations standard deviation ratio Surface Energy Balance Algorithm for Land SEBAL SEBS Surface Energy Balance System Standard Major Axis SMA SWC Volumetric soil water content (m<sup>3</sup> m<sup>-3</sup>) Tropical Applications of Meteorology Using Satellite Data and TAMSAT Ground-Based Observations VPD Vapour pressure deficit Working for Water WfW WPL Webb-Pearman-Leuning
- WUE Water use efficiency

# SYMBOLS

A	Available energy absorbed by the surface (M J $m^{-2}$ )
A <sub>s</sub>	Energy absorbed by the soil (M J m <sup>-2</sup> )
A <sub>c</sub>	Energy absorbed by the canopy (M J m <sup>-2</sup> )
Н	Sensible heat flux (W m <sup>-2</sup> )
λ <b>E</b> /LE	Latent heat flux (W m <sup>-2</sup> )
$R_n$	Net radiation (W m <sup>-2</sup> )
G	soil heat flux (W m <sup>-2</sup> )
Es	Soil evaporation (mm)
R <sub>s</sub>	Solar radiation (MJ m <sup>-2</sup> )
R <sub>ns</sub>	Incoming net shortwave radiation (MJ m <sup>-2</sup> day <sup>-1</sup> )
$R_n l$	Outgoing net longwave radiation (MJ m <sup>-2</sup> day <sup>-1</sup> )
α	Short wave surface albedo
R <sub>so</sub>	Clear-sky solar radiation (MJ m <sup>-2</sup> day <sup>-1</sup> )
R <sub>a</sub>	Extra-terrestrial radiation (MJ m <sup>-2</sup> day <sup>-1</sup> )
DoY	Julian day of year
AET	Actual evapotranspiration (mm)
ET	Evapotransipiration (mm)
Т	Transpiration (mm)
Р	Precipitation (mm)
PET	Potential evaporation (mm)
SWC	Volumetric soil water content (m <sup>3</sup> m <sup>-3</sup> )
ET0	Reference crop evaporation (mm)
gН	Conductance of heat (W $m^2 K^{-1}$ )
Δ	Slope $(s)$ of the curve relating saturation water vapour pressure to
	temperature (kPa °C <sup>-1</sup> )
D <sub>a</sub>	Water vapour pressure deficit of the air (kPa)
e <sub>a</sub>	Actual vapour pressure deficit (Pa)
e <sub>a</sub>	Saturation vapour pressure (Pa)
G <sub>c</sub>	Canopy conductance (m s <sup>-1</sup> )
G <sub>a</sub>	Aerodynamic conductance to water vapour (m s <sup>-1</sup> )
Ζ	Height of wind speed and humidity measurements (m)
d	Zero plane of displacement height (m)

z <sub>om</sub>	Roughness length governing transfer of momentum
Z <sub>OV</sub>	Roughness length governing transfer of water vapour
u	Wind speed (m s <sup>-1</sup> )
$g_s$	Stomatal conductance (m s <sup>-1</sup> )
$g_{sx}$	Maximum stomatal conductance (m s <sup>-1</sup> )
$G_s$	Surface conductance accounting for ET from the surfaces and
	transpiration (m s <sup>-1</sup> )
3	Slope (s) of the curve relating saturation water vapour pressure to
	temperature divided by the psychrometric constant (kPa K <sup>-1</sup> )
¥	Priestley-Taylor coefficient (unitless)
Ω	Decoupling factor (unitless)
ho'	Instantaneous deviation of the water density from the mean (kg $m^{-3}$ )
<i>w</i> ′	Instantaneous deviation of the vertical wind component from the mean
	(m s <sup>-1</sup> )
T'	Instantaneous deviation of air temperature from the mean (K)
T <sub>a</sub>	Ambient temperature (K)
$\rho_{h20}$	Ambient water vapour density (kg m <sup>-3</sup> )
$v_a$	Ambient air molar volume (m <sup>3</sup> mol <sup>-1</sup> )
f	Fraction of evaporation from the soil $(0-1)$
fswc	Fraction of soil evaporation using volumetric water content
f <sub>zhang</sub>	Fraction of soil evaporation using precipitation and equilibrium
	evaporation ratio
f <sub>drying</sub>	Fraction of soil evaporation using the rate of soil drying after
	precipitation
$E_{eq,s}$	Equilibrium soil evaporation (mm)
ά	A parameter controlling the rate of soil drying (day <sup>-1</sup> )
F	Function to be minimised
$Q_h$	Visible radiation reaching the canopy surface (Wm <sup>-2</sup> )
$C_n^2$	Structure parameter of the refractive index of air (m <sup>-2/3</sup> )
D	Aperture diameter of the scintillometer (mm)
L	distance (m) between the transmitter and the receiver (i.e. the path
	length)
$\sigma_{lnI^2}$	Variance of the natural logarithm of intensity fluctuations
L <sub>OM</sub>	Monin Obukhov length (m)

$\beta$ Bowen ratio	
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$Z_{LAS}$	Effective height of the scintillometer beam above the surface
	0

*w* An integration constant that is dimensionless and independent of P and

PET, and represents watershed characteristics

T\* temperature scale (K)

u \* Friction velocity (m s<sup>-1</sup>)

# **PHYSICAL CONSTANTS**

ρ	Air density $\sim 1.2$ kg m <sup>-3</sup>
$C_p$	Specific heat capacity of air $\sim 1013 \text{ J kg}^{-1} \text{ K}^{-1}$
M <sub><i>h</i>20</sub>	Molecular weight of dry air ~0.01802 kg mol <sup>-1</sup>
R	Universal gas constant ~ $8.314 \text{ J} \text{ mol}^{-1} \text{ K}^{-1}$
σ	Stefan-Boltzmann constant ~ 4.903 $10^{-9}$ MJ K <sup>-4</sup> m <sup>-2</sup> day <sup>-1</sup>
$R_{v}$	Specific gas constant for water vapour $\sim 461.5 \text{ J Kg}^{-1}$
G <sub>sc</sub>	Solar constant ~ 0.0820 MJ m <sup>-2</sup> min <sup>-1</sup>
K <sub>A</sub>	Extinction coefficient for total energy available $\sim 0.6$
$K_Q$	Extinction coefficient of visible radiation $\sim 0.6$
$L_{v}$	Latent heat of vaporisation of water $\sim 2.45~MJ~kg^{\text{-1}}$
D <sub>50</sub>	Values of water vapour deficit when stomatal conductance is equal to
	half maximum stomatal conductance $\sim 0.7$ kPa
$Q_{50}$	Visible radiation flux when stomatal conductance is equal to half
	maximum stomatal conductance $\sim 30 \text{ W m}^{-2}$
k	von Kármán constant ~ 0.41
g	Gravitational acceleration ~9.81 m s <sup>-2</sup>
γ	Psychrometric constant ~ 0.00665 kPa $^{\circ}C^{-1}$ )

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# DEDICATION

This thesis is dedicated to Lerapele and Tsepelang.

#### **CHAPTER 1: GENERAL INTRODUCTION**

#### 1.1 Background

At any given place, global and local forces influence ecosystem structure and functioning. Industrialisation has led to an increase in atmospheric CO<sub>2</sub> concentration and nitrogen fertilisation resulting in global warming and climate change. One of the positive feedbacks of the increase in atmospheric CO<sub>2</sub> concentration and nitrogen fertilization in South Africa has been woody thickening in the savanna and Albany Thicket (AT) biomes and woody encroachment in grasslands (Wigley et al., 2010; Buitenwerf et al., 2012; O'Connor et al., 2014; Stevens et al., 2016). Additionally, decisions on land use and land cover influence ecosystem functioning. Globally, grasslands cover approximately 40% of the terrestrial land surface and play a critical role in the provision of ecosystem services such as food, water supply, forage, biodiversity conservation and carbon sequestration among others (Ahlering et al., 2016; Forrestel et al., 2017; Carlsson et al., 2017). In South Africa, the grassland biome comprises about 27.9% of the total terrestrial biomes of the country (Van Wilgen et al., 2012) and almost 30% of the grassland biome has been permanently transformed due to cultivation, plantation forestry, urbanisation and mining (Mucina et al. 2006).

The Eastern Cape province of South Africa is predominantly grassland (Mucina et al., 2006) with livestock and wildlife ranching being the main agricultural activities. Woody encroachment into the grasslands in the Eastern Cape manifests in two main forms, namely woody encroachment by native species such as Vachelia karroo and Searsia spp. (O'Connor et al., 2014) and increases in invasive alien plants (IAPs), predominantly Australian acacias such as Acacia mearnsii and A. dealbata (van Wilgen et al., 2008; Kotzé et al., 2010). At the same time the development of human settlements, forestry plantations and large scale commercial food crop farms in the Eastern Cape have a bearing on ecosystem functioning, especially the water and energy fluxes. These changes have directly impacted on herbage (grass) production for livestock and wildlife ranching, thereby affecting livelihoods of farming communities (van Wilgen et al., 2008). Functional rangelands also provide other ecosystem services such as water supply and storm-flow reduction. Within the broader context of climate change, better management of available water is essential in pursuit of integrated water resources management (IWRM, Agarwal et al., 2000) and also in improving food production systems (Molden et al., 2010). Evapotranspiration (ET) or latent heat flux (LE) forms the biggest flux of the hydrological cycle after precipitation yet it is not well understood (Liou &

Kar, 2014; Amatya et al., 2016). Therefore, in the Eastern Cape, there is a need to explore better ways of managing rangelands that are undergoing changes in order to optimise herbage production. In addition, within the purview of climate change, understanding of water and energy fluxes in rangelands is critical to improve knowledge on ecosystem functioning so as to deal with the consequences of climate change.

The Grassland and the Albany Thicket (AT) Biomes in the Eastern Cape provide interesting opportunities to study the dynamics in ecosystem processes in the rangelands. The ability of the Grassland Biome in the Eastern Cape to support requisite ecosystem services such as grazing is being undermined by the spread of IAPs mainly Australian acacias (van Wilgen et al., 2008). Hence, there is a need to fully understand the effects of A. mearnsii on grass production in order to optimally manage the invaded landscape. The AT Biome which covers about 2.3% of the terrestrial biomes of South Africa (van Wilgen et al., 2012) has recently received renewed interest owing to the presence of Portulacaria afra (spekboom), which is believed to be a net carbon sink (Mills & Cowling, 2006) and hence very important in atmospheric CO<sub>2</sub> reduction. This has led to widespread environmental plantings of P. afra in order to sequester CO<sub>2</sub>. The AT has also been recognised as a centre of biodiversity and endemism for karroid succulents (Hoare et al., 2006). Hence, it is prudent to have a deeper understanding of ecological processes in this biome in a context of accelerated global environmental changes associated with climate change. A number of studies have been conducted in the AT of South Africa and these have mainly been focused on carbon sequestration within the broader context of the clean development mechanism (CDM), the distribution of particular species and the infiltration and runoff dynamics (Mills & Cowling, 2006; van Luijk et al., 2013; Becker et al., 2015). Hence, little attention has been given to water vapour and energy dynamics of the biome. However, the recent installation of an eddy covariance (EC) in the AT biome at a site dominated by the facultative Crassulacean Acid Metabolism (CAM) photosynthesising *P. afra* has provided an opportunity to further study water vapour and energy fluxes over the AT dominated by P. afra. This is crucial as it will help to calibrate and validate ET models for the biome.

#### 1.2 Woody encroachment and herbage (grass) production

Arguably, IAPs are becoming a pervasive force for global change as they often alter the structure and functioning of ecosystems. There is emerging evidence that IAPs have sometimes irreversibly changed the ecosystems from their baseline (Hobbs et al., 2014). At a global scale,

most biomes are being transformed by Australian acacias (Kull & Rangan, 2008; Kull et al., 2011; Le Maitre et al., 2011). In South Africa, over 70 species of these acacias (wattles) were introduced as early as the 19th century (van Wilgen et al., 2011). Of these, Acacia mearnsii (De Wild) has become an aggressive invader in the grasslands of the Eastern Cape. It is well established that A. mearnsii alters soil properties which may undermine the growth of indigenous vegetation in the long run (Moyo & Fatunbi, 2010; Le Maitre et al., 2011; Boudiaf et al., 2013; Souza-Alonsoet al., 2013; Gonzalez-Muñoz et al., 2014; Lazzaro et al., 2014). Ecosystem repair after clearing of A. mearnsii is influenced by the capacity of both biotic and abiotic factors to enhance production. 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 land restoration efforts are underpinned by an appreciation of soil characteristics (Costantini et al., 2016). Soil indicators could be vital in assessing the degree of ecosystem or rangelands change due to IAPs. Soils provide essential nutrients that support biomass production, which is critical for the supply of ecosystem services such as forage resources (Smith et al., 2015). In addition, soils are strongly coupled with biogenic material and energy recycling. Efforts to rehabilitate degraded land should consider specific soil characteristics that can be used as a prognosis of landscape recovery or deterioration (Costantini et al., 2016). By analysing species richness and cover, Ndhlovu et al. (2016) found that clearing of the invasive Prosopis spp. restored indigenous species richness to the pre-invasion stage. From a rangeland management perspective, understanding of physico-chemical characteristics of the soil and attendant biomass production within the system may be useful in informing rehabilitation. Depending on the extent of disturbance, a suite of biotic and abiotic interventions may be required to expedite recovery. Therefore, it is vital to explore the extent of changes in the soil as a vegetation growth substrate in areas that have been invaded or cleared of IAPs, and to explore the ability of grass biomass recovery as a result of the clearing of A. mearnsii in the grasslands of the north Eastern Cape.

#### **1.3 Managing IAPs and ecosystem restoration**

The problem of woody thickening has been recognised in South Africa and is coupled with global fertilization by carbon and nitrogen (Buitenwerf et al., 2012; Stevens et al., 2016) There is emerging evidence that IAPs alter biodiversity and tend to use more water compared to indigenous species (Le Maitre et al., 2002; Holmes et al., 2008; Clulow et al., 2011; Meijninger

& Jarmain, 2014). Hence, the South African government has responded through massive IAPs clearing efforts at an annual cost of US\$100 million under the auspices of the Working for Water (WfW) programme in order to restore ecosystems (Turpie et al., 2008; Wilcox, 2010; van Wilgen et al., 2012). The clearing strategy revolves around clear felling and leaving the remains to rot in situ. Despite this massive investment, there has been only moderate success in eradicating these IAPs to gain the lost ecosystem services such as grazing land. For example, several studies have reported the slow pace of clearing in prioritised areas when compared to resources invested (Beater et al., 2008; McConnachie et al., 2012; van Wilgen et al., 2012). At the same time, it has been argued that linking removal of IAPs with concomitant water saving is a daunting task (Gorgens & vanWilgen, 2004; Wilcox, 2010; Doody et al., 2011) since the storage and movement of water in the soil profile is not well-known and is the least understood aspect of the hydrological cycle (Jewitt, 2006). Doody et al. (2011) concluded that demonstrating a decline in ET after the removal of IAPs was not conclusive evidence to show that the objectives of water saving have been met. This could only be demonstrated if the replacement vegetation or cover surface has lower ET than IAPs. Hence, there are possibilities of missed opportunities provided by an invaded landscape if the current clear fell strategy continues. If no replacement species are intentionally introduced after clearing (as is most often the case in the north Eastern Cape), it might be difficult to claim water salvage. In addition, Wilcox (2010) reported that there is scant evidence that transforming grasslands into shrublands lead to appreciable changes in stream flow unless degradation processes are also taking place because under degradation conditions runoff tends to be higher. Therefore, a combination of the slow pace of clearing using the 'clear fell' approach and controversies around linking water saving to removal of IAPs necessitate the need to develop innovative approaches for managing invaded rangelands in order to optimise landscape use.

#### 1.4 Improving water availability for agriculture

Land cover changes that are linked to development initiatives present challenges for integrated land and water resources management in the Eastern Cape. IWRM is a unifying paradigm for sustainable land and water resources management (Agarwal et al., 2000). Most water management institutions, as reported in the literature on IWRM, tend to focus on blue water (water flowing in rivers and groundwater) and neglect green water which is used in biomass production and ET (Agarwal et al., 2000; Rockstrom & Gordon, 2001; Gordon et al., 2003). 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 etal., 2011; Hoff et al., 2010; McMahon et al., 2013; Liou & Kar, 2014), making 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 stretched their blue water resources to the limit and so improving green water management will be critical in improving global production systems (Hoff et al., 2010; Liu & Yang, 2010). Therefore, management of green water flows holds significant potential for improving water productivity and protection of vital ecosystems (Molden et al., 2010). Hence, understanding of ET in the Grassland and AT Biomes of the Eastern Cape will provide the basis for improved management of green water flows.

#### **1.5 Determining green water flows**

One of the challenges in achieving IWRM is a paucity of information on eco-hydrological processes in many un-gauged catchments of South Africa and elsewhere. For the Eastern Cape, an appreciation of green water flows or ET will contribute immensely to data requirements for IWRM. Hence, responsive water management should start with an understanding of water use at a landscape scale. Often, the fluxes attributable to the different land cover types in a catchment are unknown. Thus to fully account for water use in a catchment, the consumptive nature of different land cover types must be determined. However, measuring ET or its energy equivalent, LE, is difficult and costly (Amatya et al., 2016). But knowledge of ET in different land cover classes will contribute to data requirements for IWRM in a context of global changes. In South Africa, a number of studies have been undertaken to measure ET using surface layer scintillometry (Savage et al., 2004, 2010; Dzikiti et al., 2013), Bowen ratio (Euser et al., 2014), open top chambers (Finca et al., 2015) and eddy covariance systems (Jarmain et al., 2004; Clulow et al., 2011, 2015). With the exception of Finca et al. (2015), these studies were conducted in relatively wetter environments compared to the Eastern Cape. Although the Finca et al. (2015) study was conducted in the Eastern Cape, the equipment used created an artificial environment and the ET derived is subject to a large degree of uncertainty. An earlier study had indicated a decrease in the intensity of 10-year high rainfall extremes in parts of the Eastern Cape and Lesotho (Mason et al., 1999). Based on climate change models, a decline in annual rainfall in the Eastern Cape and parts of eastern South Africa is projected (Engelbrecht et al., 2009). At the same time, observed data in the region showed weak changes in precipitation between 1962 and 2010 except for one station in the northern coast that showed significant decrease in the number of rainy days during this period (MacKellar et al., 2014). Hence, in light of these observed or projected changes and dynamics in land cover change, it is important to benchmark ET from several studies using scientific-grade research instruments in order to better deal with the projected climate trajectories in the Grassland and the AT Biomes. Hence, full knowledge of ET is critical in developing requisite information for integrated land and water resource management.

Given difficulties in measuring ET, modelling becomes relevant in order to generate data required for planning and equitable resource allocation purposes. ET modelling is based on several approaches including water balance, energy balance, temperature, and radiation models (Fisher et al., 2011). Consequently, a number of approaches have been developed to try and characterise the exchange of water vapour 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 & Kar, 2014). Much of ET modelling is based on the classical works of Thornthwaite, Priestley and Taylor and Penman-Monteith (Fisher et al., 2008). It is well established that of these methods, the Penman-Monteith (PM) equation 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 a 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). The PM approach evolved as a big leaf model (Penman, 1948; Monteith, 1965) that treated a canopy as a uniform single surface/leaf. Big leaf (single layer/ source) models are widely used because they are highly simplified and yet physically sound (Overgaard et al., 2006). Some of the single source energy balance models that have been applied in southern Africa include the Surface Energy Balance Algorithm for Land (SEBAL; Meijninger & Jarmain, 2014) and Surface Energy Balance System (SEBS; Rwasoka et al., 2011; Gibson et al., 2011; 2013). Recent versions of SEBAL are strongly controlled by intellectual property restrictions and are therefore not available for un-affiliated researchers. In comparison, SEBS was found inappropriate because of its sensitivity to a number of parameters (Gibson et al., 2011). Owing to the theoretical soundness of the PM model, its further exploration was considered to be useful particularly in the Grassland and AT Biomes.

#### 1.5.1 Introduction to the Penman-Monteith (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:

$$\lambda E = \frac{\Delta A + (\rho C_p) D_a g H}{\Delta + \gamma \left(\frac{g H}{G_a}\right)}$$
[1.1]

where  $\lambda E$  is latent heat energy (Wm<sup>-2</sup>) or evapotranspiration (mm), gH is the conductance of heat (W m<sup>2</sup> K<sup>-1</sup>), A is the available energy absorbed by the surface (W m<sup>-2</sup>), i.e. net radiation  $(R_n)$  minus soil heat flux (G),  $\gamma$  is the psychrometric constant (kPa °C<sup>-1</sup>),  $\rho$  is air density (kg m<sup>-3</sup>),  $C_p$  is specific heat capacity of air (J kg<sup>-1</sup> K<sup>-1</sup>),  $\Delta$  is the slope (s) of the curve relating saturation water vapour pressure to temperature (kPa °C<sup>-1</sup>),  $D_a$  (kPa) is  $e * (T_a) - e_a$  which is the water vapour pressure deficit 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<sup>-1</sup>) to water vapour which is determined by wind speed. Equation 1.1 was reduced by assuming  $gH = G_a$  (Penman, 1948; Whitley, 2011) to give the Penman equation:

$$\lambda E = \frac{\Delta A + (\rho C_p) D_a G_a}{\Delta + \gamma}$$
[1.2]

Monteith (1965) changed Equation 1.2 to incorporate the biological mechanism of the stomata. This was achieved by recognizing 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:  $\gamma\left(\frac{gH}{g_v}\right) = \gamma\left(\frac{G_a}{G_a + g_s}\right) = \gamma\left(1 + \frac{G_a}{g_s}\right)$  [1.3]

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:

$$\lambda E = \frac{\Delta A + (\rho C_{\rm p}) D_a G_a}{\Delta + \gamma \left(1 + \frac{G_a}{G_s}\right)}$$
[1.4]

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:

$$\lambda E = \frac{\rho C_p D_a G_s}{\gamma}$$
[1.5]

On the other hand, over moist surfaces such that  $G_a \ll G_s$ , 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 vapour pressure deficit (VPD) or  $D_a$ :

$$\lambda E = \frac{\Delta A}{\Delta + \gamma}$$
[1.6]

#### 1.5.2 Partitioning transpiration and soil evaporation

It should be noted that  $G_s$  as initially conceived by Monteith (1965) in equation 1.4 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 thesis 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 1.1 presents a simplified diagram to show a layer of resistances to evapotranspiration.



Figure 1.1. 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.

#### 1.6 Parameterising the Penman-Monteith equation in South Africa

Despite its robustness, there have been limited attempts at parameterising the PM equation in South Africa. Dzikiti et al. (2014) parameterised canopy conductance to calculate T and  $E_s$ using a modified Priestley & Taylor (1972) equilibrium ET equation. This approach entailed optimising six model parameters, making the method overly complex. In addition, soil evaporation was modelled with the assumption that soil water content was not limiting. Whilst this could have been true with respect to their study site in the Western Cape's Fynbos biome, such an approach is inappropriate for the water-limited systems of the Eastern Cape. In the Eastern Cape, rainfall has a strong summer seasonality and causes rapid positive feedback on soil water content during precipitation events followed by long periods of soil drying to the extent that  $E_s$  becomes negligible. An appropriate model for such drier areas should be able to reproduce the rate of soil drying after precipitation events in order to accurately predict  $E_s$ . Dzikiti et al. (2014) also used a small calibration window (5 days) which may not be representative of average conditions. Therefore, there is need to parameterise the PM in other biomes in order to easily derive ET on a large scale. In addition, the development of simplified algorithms based on the robust PM equation may be useful in providing accurate ET in semi-arid areas with scarce micrometeorological data such as the Eastern Cape.

#### 1.7 Factors determining water and energy flux partitioning

ET is a complex process tightly coupled with vegetation phenological characteristics such as leaf area, density and stomatal conductance as well as climate factors such as radiation and soil moisture. Therefore, it is important to fully appreciate the partitioning of  $R_n$  into sensible (H), latent (LE) and soil heat flux (G) in research on the local and regional climate system. More so, improved knowledge on factors modulating the partitioning of energy and water vapour fluxes is important in a context of environmental changes which in turn influence water and energy balance (Jia et al., 2016; Odongo et al., 2016). Studies on energy partitioning are limited in Africa, largely because of limited field observation instruments (Jia et al., 2016; Odongo et al., 2016). Recent studies have largely been related to energy balance closure in West Africa (Bagayoko et al., 2006) and southern Africa (Majozi et al., 2016). A few studies have focused on the integrated impact of biophysical factors on energy fluxes partitioning (for example, Mamadou et al., 2016; Odongo et al., 2016) and these studies were conducted in West Africa. However, understanding factors modulating energy partitioning may help to anticipate and manage impacts of climate change (Jia et al., 2016). In a context of global environmental changes, it is useful to fully appreciate the main factors controlling energy partitioning in important biomes of southern Africa such as the AT.

#### 1.8 Evapotranspiration in water and energy limited ecosystems

The Budyko hydro-meteorological framework (Budyko, 1974) is useful in studying the effects of global change on water resources. The framework is based on the assumption that mean annual ET is controlled by long term mean precipitation (P) and potential ET (PET) (Wang et al., 2016). As such long term evaporation on large basins could be calculated based on the relationship between the evaporative index  $\left(\frac{ET}{P}\right)$  and the dryness index  $\left(\frac{PET}{P}\right)$ . Hence in water-limited systems or dry conditions, ET approaches P and under very wet conditions; ET will

approach PET, becoming limited by energy availability. The Budyko framework is expressed as:

$$\frac{ET}{P} = \left[\frac{PET}{P} tanh\left(\frac{PET}{P}\right)^{-1} \left(1 - \exp\left(\frac{PET}{P}\right)\right)\right]^{0.5}$$
[1.7]

The Budyko framework assumes steady state conditions and that climate variations can explain changes in the catchment water balance (Gao et al., 2016). Hence the original framework is sound when examining the impacts of climate change on catchment water balance but it does not deal with other important catchment properties, such as characteristics of the groundwater system, vadose zone properties and vegetation (Du et al., 2016). Recent research on the Budyko framework has attempted to parameterise these important catchment characteristics that were ignored by the original framework (Zhang et al., 2001, 2004; Chen et al., 2015; Moussa & Lhomme, 2016). These new insights allowed the Budyko framework to be applicable in nonsteady state situations and in smaller catchments, in order to understand the dynamics in catchment water balance. Land cover change is threatening grasslands of the Eastern Cape and this is likely to have a positive feedback on catchment water balance. In a context of data scarcity, the new variants of the Budyko framework may be useful in tracing the impact of nonsteady state conditions related to catchment characteristics on changes to hydrological fluxes such as ET. There has been limited research on the use of Budyko framework in southern Africa. For example, Kapangaziwiri et al. (2009) applied the Budyko framework to help inform hydrological regionalisation of quartenary catchments behaviour while Chapter 8 of this thesis (Gwate et al., 2016) used the relationship between the mean annual evaporative index and precipitation to examine the impact of land cover change on ET. Quaternary catchment is the main water management unit in South Africa and denotes a fourth order catchment in a hierarchal classification system in which a primary catchment is the major unit. Therefore, parameterising integrated catchment characteristics may be useful in understanding dynamics in hydrological fluxes at a quartenary catchment scale.

#### 1.9 Scope of this thesis

From the foregoing sections, a number of outstanding issues and challenges in the management of invaded rangelands, as well as measuring and modelling water vapour fluxes were identified. Conventional thinking and practice in South Africa is that IAPs are undesirable and at best have to be eradicated as they have higher water use than indigenous species. Hence, the current management effort for invaded landscape in South Africa has been clear felling under the auspices of the WfW programme in order to eradicate these plants. However, there has been
little progress to this end (Beater et al. 2008; McConnachie et al. 2012; van Wilgen et al. 2012). At the same time, there has been little research effort in developing management approaches to promote multiple benefits of the invaded landscape. Arguably, IAPs bring about a host of opportunities in such landscapes. Hence, this thesis seeks to address this gap by determining the influence of *A. mearnsii* on rangelands and exploring optimum management strategies for the selected areas. Further, this thesis explores whether grasslands invaded by IAPs such as *A. mearnsii* can recover autogenically after clearing. This was achieved by evaluating abiotic soil properties and modelling grass aboveground net primary production (ANPP) to uncover evidence of recovery.

In addition, the thesis also tests the suitability of conventional meteorological data collected from scientific grade Automatic Weather Stations (AWS) for modelling ET in semi-arid areas compared to ET derived from micrometeorological methods such as Eddy Covariance (EC) system and Large Aperture Scintillometers (LAS). ET is one of the processes that gives an insight into ecosystem functioning. However, in data scarce areas, characterising ET is a huge challenge. This thesis calibrated and validated the Penman-Monteith-Leuning (PML, Leuning et al., 2008; Morillas et al., 2013) model in the Eastern Cape so that fine resolution ET can be derived in data scarce areas. The thesis further improves a single layer PM based model described by Palmer et al. (2014), conveniently called the Penman-Monteith-Palmer (PMP) in this thesis, to enable it to also account for  $E_s$ . In addition, simplified algorithms for predicting ET in data scarce areas over selected vegetation types were developed in order to circumvent the problem of data paucity. Further, a variant of the classical hydro-meteorological Budyko framework is applied to appreciate the impact of land cover change on ET at an un-gauged quaternary catchment.

#### 1.9.1 Aim of the study

The aim of the study was to contribute towards better management of rangelands by understanding the dynamics in rangeland grass production and water use. Pursuant to this, specific objectives of the study were:

- 1. To determine the impact of *A. mearnsii* invasion on rangelands grass production and to explore optimal ways of managing rangelands invaded by IAPs such as *A. mearnsii*.
- To understand the dynamics in water vapour and energy fluxes on un-invaded examples of Grassland and AT Biomes, and to explore biophysical factors influencing the partitioning of these fluxes in the latter.

- 3. To test the ability of the Penman-Monteith-Leuning (PML) ET model to reproduce observed ET over the AT Biome which is strongly believed to be controlling water use through stomatal behaviour.
- 4. To validate the PML and the PMP ET models in the grassland biome using a large aperture scintillometer (LAS).
- 5. To develop simplified algorithms for estimating actual ET in semi-arid data scarce landscapes of the Eastern Cape.

6. To evaluate the link between land cover change and ET at a quaternary catchment scale. Activities to accomplish these objectives included:

- a) Field surveys and application of requisite techniques to characterise biophysical attributes of invaded landscapes.
- *b)* Analysis of selected soil variables and examining the extent to which they were altered by *A. mearnsii*.
- c) Site selection and micrometeorological experiment set up (Scintillometer and eddy covariance system).
- d) Collection of meteorological data for forcing the ET models.
- e) Comparison of the measured and modelled ET in order to evaluate the three ET models.
- f) Downloading remote sensing data and GIS analysis.

# 1.9.2 Thesis outline

The thesis is organized into 9 chapters and Figure 1.2 shows how the scope of the thesis will be addressed. The first part (Chapters 2 and 3) deals with the impact of *A. mearnsii* on rangeland grass production and also explores optimal ways of managing invaded landscape. Chapter 2 explores the influence of *A. mearnsii* on rangeland production in three quaternary catchments in the Eastern Cape. The objective of this chapter is to demonstrate the extent to which *A. mearnsii* influences grass production. This is achieved by analyzing the extent to which soil properties have been modified by the invasion of *A. mearnsii* and also by modelling the aboveground grass biomass in areas cleared of *A. mearnsii*. Specifically, Chapter 2 addresses objective 1 and contributes towards a better understanding of the dynamics in rangeland production in the broader scope of the thesis.

Chapter 3 seeks to contribute to optimum ways of managing rangelands affected by IAPs and contributes to objective 1 with respect to rangeland production. The aim of this chapter is to understand the biophysical properties of *A. mearnsii* in grasslands as they relate to grass

production and to explore management implications with the view to preparing a policy brief. Biophysical attributes of *A. mearnsii* related to aboveground biomass (AGB), leaf area index (LAI) and normalized difference vegetation index (NDVI) as well as grass cover under *A. mearnsii* canopies are examined. This understanding could form the basis for future research on management of infested rangelands.

The second part (Chapters 4 - 8) is devoted to dynamics of water vapour and energy fluxes in rangelands. Chapter 4 presents results of ET measurement in the AT biome and it essentially addresses objective 2 and contributes to a better understanding of dynamics in water vapour and energy fluxes over a leaf succulent shrub (*Portulacaria afra*) which is believed to be a net carbon sink. The chapter also evaluates environmental factors affecting ET and energy fluxes over the Thicket.

Chapter 5 tests the ability of the PML ET model to reproduce observed ET over a system believed to exercise strong control over the ET process through stomatal behaviour. Consequently, it is devoted to calibrating and validating the PML in the Albany Thicket Biome of South Africa. The chapter contributes to a better understanding of the complexities around modelling ET in environments characterised by strong stomatal control of ET. The chapter addresses objectives 2 and 3.

Chapter 6 presents results of measuring and modelling ET on grassland. The objective of this chapter is to compare the performance of the PMP and PML models over grassland using ET derived from AWS data and MODIS LAI and albedo, with validation using data from a LAS. Chapter 6 addresses objective 2 and contributes to an understanding of dynamics in water use of the grassland.

Chapter 7 is devoted to efforts to improve the single layer PMP model by translating it into a two-layer model through the incorporation of a soil evaporation component. In addition, algorithms were developed to help predict ET in data scarce catchments of the Eastern Cape. This contributes to the thesis by developing simple but accurate algorithms for estimating ET in semi-arid and data scarce areas and it addresses objective 5.

Chapter 8 addresses the link between land use change and ET in sub humid grasslands of South Africa affected by *A. mearnsii*. It links land use change to the evaporative index at a quaternary

catchment scale and also it determines the catchment parameter which is used to indicate impacts of land cover change on hydrological fluxes. The chapter contributes to objective 6 and presents evidence of ET changes due to dynamics in catchment characteristics by applying a variant of the classical Budyko framework. Finally, Chapter 9 provides a synthesis of the study, highlighting major findings and the optimal ways of managing invaded landscapes in order to enhance net benefits to the communities. The implications of the results are interpreted and gaps and future research possibilities are identified.



The effects of *Acacia mearnsii* (black wattle) on soil physicochemical and grass biomass production in a South African semiarid grassland: implications for rangeland rehabilitation

Exploring the invasion of rangelands by *A. mearnsii*: biophysical characteristics and management implications

Water vapour and energy fluxes over the Albany Thicket of the Eastern Cape, South Africa

Modelling evapotranspiration using a modified Penman-Monteith equation and MODIS data over the Albany Thicket in South Africa

Measuring and modelling ET in a South African grassland: comparison of two improved Penman-Monteith formulations

Estimating ET in a drylands: scaling potential to actual evaporation and the role of soil evaporation

Exploring dynamics of ET trends in selected land cover classes in a sub humid region of South Africa

Conclusions and recommendations for further study

Figure 1.2. Framework for addressing the scope of the thesis.

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# CHAPTER 2: 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

This chapter will be submitted to a suitable journal.

OG conducted all of the field campaigns, analysed the data and wrote the text in this chapter.

# 2.1 Abstract

Globally, grasslands are under threat from woody encroachment by invasive alien plants (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. The study sought to determine the effect of A. mearnsii clearing on soil physicochemical properties and grass canopy cover on rangelands. Soil samples at two depths were collected from three A. mearnsii invasion statuses at four study sites in the north Eastern Cape and analysed for P, K, N, Mg, Ca, Zn, acid saturation, CEC, bulk density, pH and total cations. Using the line transects and the disc pasture meter (DPM) approaches, equations were developed to predict grass aboveground net primary production (ANPP) in areas cleared of A. *mearnsii*. The results show that A. *mearnsii* significantly (p < 0.05) altered most of the physicochemical soil characteristics which in turn impact grass rangeland production. Predicted grass ANPP from sites cleared of *A. mearnsii* ranged from 270 to 348 g m<sup>-2</sup> yr<sup>-1</sup> and this ANPP was factored by rainfall and nutrient gradients. These production rates were similar to those from uninvaded landscapes in South Africa, suggesting that background grass production can still be attained even if clearing is not accompanied by active soil management, indicating that abiotic recovery thresholds have not been surpassed at the study sites. Management of invaded rangelands should be informed by an understanding of the likely modifications of soil properties by the wattle based on an appreciation of local soil background characteristics. The allometric equations developed for ANPP prediction are easy to use and may enable farmers to estimate forage availability as well as fuel loads using non-destructive methods in rangelands cleared of A. mearnsii to inform decisions on grazing management.

*Keywords:* A. mearnsii, aboveground net primary production, grass cover, principal components analysis, rangeland recovery, soil properties

# **2.2 Introduction**

Globally, most biomes including grasslands are under threat from IAPs such as Australian acacias (Kull & Rangan, 2008; Kull et al., 2011; Le Maitre et al., 2011). Biological invasions are a pervasive force for global change and they often have deleterious ecological impacts. Australian acacias have spread to most parts of the world mainly between 35° North and 40° South (Kull & Rangan, 2008). About 60% of the Grassland Biome in South Africa has been permanently altered (Little et al., 2015). This biome is crucial for livestock and wildlife ranching among other ecosystem services. While some communities respond to the

introduction of Australian acacias by taking opportunities associated with them, others view them as undesirable and therefore, these acacias have to be removed (Kull & Rangan, 2008; Kull et al., 2011). For example, the South African government has undertaken a major strategic IAPs clearance initiative under the auspices of the Working for Water Programme (Turpie et al., 2008; Wilcox, 2010). In South Africa, concerns around IAPs are well documented. These mainly revolve around emerging evidence that they use more water than indigenous species (Le Maitre et al., 2002; Turpie et al., 2008; Clulow et al., 2011; Meijninger & Jarmain, 2014) and that they undermine biodiversity (Holmes et al., 2008; van Wilgen et al., 2011). However, there is paucity of studies that have attempted to investigate the influence of the invasive A. mearnsii on grass ANPP in rangelands in South Africa. The north Eastern Cape grasslands are under threat from A. mearnsii among other IAPs. Local communities of the north Eastern Cape are essentially dependent on livestock and crop production, but their land is under threat from IAPs especially A. mearnsii. The IAPs impact heavily on the capacity of any biome to provide requisite ecosystem services. Ecosystem services relate to benefits accrued to society as a result of the state and quantity of natural capital (MA, 2005). They include regulating, provisioning, cultural and supporting services. For ranchers this will mainly imply availability of forage resources. However, it should be acknowledged that IAPs also provide a host of other ecosystem services such as carbon sequestration, wood, fencing material and shed amongst others.

In order to effectively manage land affected by IAPs, it is crucial to understand the intricate forces that create particular disturbances which ultimately influence ecosystem functioning (Le Maitre et al., 2011). The impact of invasive Australian acacias is well documented in literature (Moyo & Fatunbi, 2010; Le Maitre et al., 2011; Boudiaf et al., 2013; Souza-Alonsoet al. 2013; Gonzalez-Muñoz et al., 2014; Lazzaro et al., 2014). The potential for ecosystem repair after clearing of invasive species is influenced by the capacity of both biotic and abiotic factors to enhance production. 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. Although, it has been recognised that restoring degraded land is an elusive issue, most management efforts 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). Soils are strongly coupled with biogenic material and energy recycling. As such efforts to rehabilitate degraded land should consider specific soil characteristics that are capable to be used as a prognosis of landscape recovery or deterioration (Costantini et al., 2016). Therefore, from a rangeland management perspective, intervention efforts should be informed by an understanding of physico-chemical and biological characteristics of the soil and attendant biomass production within the system. Depending on the extent of disturbance, a suite of biotic and abiotic interventions may be required to expedite recovery.

One indicator of rangeland production is the aboveground primary net production (ANPP) or standing biomass of forage resources. ANPP relates to the quantity of aboveground standing plant biomass or carbon accrued over a specific time period such as over a growing season (Byrne et al. 2011). Within the broader context of IAPs clearing in South Africa, there is need to quantify herbage recovered after removal of the plants in order to better understand the economics of clearing from a ranching perspective. Hence, a better understanding of the dynamics in herbage or grass ANPP 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., 2011, 2016). In addition, reduction in the overstorey 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 overstorey 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 ANPP 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. The Eastern Cape is predominantly grassland and is under threat from A. mearnsii and hence it provides an interesting opportunity to verify whether grasslands affected by A. mearnsii respond in a similar manner to the Nama Karoo and Savanna Biomes and also to develop and test parsimonious allometric relations for predicting grass ANPP after the clearing of *A. mearnsii* to inform grazing management.

The aim of this work was to understand the effects of *A. mearnsii* on soil physical (bulk density) and chemical (P, K, N, Mg, Ca, Zn, acid saturation, CEC, pH and total cations) properties as well as how its clearing influenced aboveground herbage production. Firstly, the extent to which soil chemical properties have been modified by *A. mearnsii* invasion was determined. From a rehabilitation perspective, this is important since results should give an insight to the ability of the system to self-regenerate or the need for abiotic and biotic interventions to facilitate ecosystem recovery. Secondly, total grass dry biomass or ANPP in areas cleared of *A. mearnsii* was modelled to uncover the effect of *A. mearnsii* clearing on herbage recovery in the Grassland Biome.

#### 2.3 Material and methods

#### 2.3.1 Study area

The study is located in the north Eastern Cape Province of South Africa. This region predominantly lies in the former Transkei/ homelands, which were overcrowded and overstocked from as early as 1913 with the passage of the Native Land Act (Palmer & Bennett, 2013). The study is located in three quaternary catchments of Mzimvubu-Keiskama water management area  $(31^{\circ}04 - 31^{\circ}42 \text{ S}, 27^{\circ} 04 \text{ E} - 28^{\circ} 16 \text{ E})$ . Quaternary catchment is the main water management unit in South Africa and denotes a fourth order catchment in a hierarchal classification system in which a primary catchment is the major unit. Two of these quaternaries (T12A and S50E) lie on communal lands while T35B is dominated by freehold land tenure holdings (Fig. 2.1). Acacia mearnsii has reportedly been introduced in South Africa from as early as the 19<sup>th</sup> century (van Wilgen et al., 2011). Owing to emerging evidence that IAPs affect biodiversity and use more water than indigenous species, strategic efforts have been ongoing since 1995 to clear the land of IAPs. The selected sites have experienced varied success to clearing of IAPs with the commercial farming area having had a better success rate and clearing in the study areas started circa 2005. The study sites lie predominantly on the southern Drakensberg highland grassland bioregion (Mucina et al., 2006). The selected sites were dominated by Sporobolus africanus, Heteropogon contortus, Eragrostis plana and Aristidia junciformis grass swards. The geology of the area comprises of sandstones of the Clarens formation and sandstones, silt stones and mudstones of the Elliot formation. The area is characterised by wet summers and dry winters with long-term mean annual rainfall for respective sites ranging from 655 – 786 mm (Schulze, 1997). Across the study sites, the main economic activities are livestock (cattle, sheep, goats and poultry) and rain-fed annual crop production.



Figure 2.1. Map of the study area showing the three quaternary catchment study sites.

#### 2.3.2 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 site. For each invasion class, three replicate samples were collected using a hand-held 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 and analysed for P, K, N, Mg, Ca, Zn, acid saturation, CEC, pH, total cations and bulk density which represented physical characteristics. 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.

#### 2.3.3 Soil statistical analysis

In order to reduce errors, soil samples data were analysed using a general 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 Components Analysis (PCA) with an orthogonal rotation of the axes (varimax rotation) was performed to identify the main factors accounting for observed responses in soil status across the sites in the R software (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 & 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 1.

# 2.3.4 Grass aboveground net primary production and grass cover estimation in cleared areas

This study applied two independent methods of determining ANPP or total dry biomass. The study calibrated the DPM (Bransby & Tainton, 1977; Zambatis et al., 2006) in commercial and communal lands. At the same time, land surface cover and ANPP along line transects were estimated in areas cleared of IAPs (Flombaum & Sala, 2007).

# 2.3.5 Line transects and ANPP prediction

Flombaum & Sala (2007) suggested a non-destructive and rapid method for determining the ANPP in grasslands as an alternative to harvest techniques whereby dry matter biomass is estimated using variables that correlate with it, such as vegetation cover. Following this, grass canopy cover data were collected from a total of 21 transects in 2014, 2015 and 2016 at the end of the growing season during the month of May. It should be noted that the study could not exclude the sample sites from grazing. Along each 100 m transect, ANPP was collected after every 20 m from a 0.2 m<sup>2</sup> quadrat. In each quadrat, percentage cover was visually estimated based on the quadrat area covered by grass. Grass samples from each quadrat were later oven dried at 37°C for three days to obtain dry matter weight. Simple linear regression was prepared to predict grass dry matter biomass from grass cover data. Along each transect, surface cover of any form encountered was estimated as a proportion of the distance covered by a particular cover type to the total length of the transect (Flombaum & Sala, 2007).

# 2.3.6 Calibrating the DPM and ANPP prediction

In order to explore recovery of rangelands after clearing of *A. mearnsii*, a total of six grazing exclosures (2.25 m<sup>2</sup>) were established in cleared areas where soil samples were collected (in T12A and T35B) and two additional exclosures were established in two cleared areas at quaternary catchment S50E. Owing to logistical challenges, soil samples were not collected in the latter catchment and it was reckoned that exclosures will still be useful in demonstrating grass recovery after the removal of IAPs. The exclosures were established during the month of June 2014 and all exclosures were initially clipped to 2 cm above the soil surface. At the end of the growing season in May 2015 and 2016, the DPM was applied at nine points within each exclosure and the DPM settling height recorded for each throw followed by clipping the grass to 2 cm. The clipped grass was later oven dried at 37°C for three days to get the dry matter weight. Simple linear regression of dry matter biomass (ANPP) against the DPM settling height was used to calibrate the DPM. Based on the calibration, ANPP was estimated using the mean DPM settling height for each respective site.

#### 2.4 Results

#### 2.4.1 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 2.1) and this allowed for further analysis of the between subject effects.

Table 2.1. Effects of sites, invasion status and interactive effects of invasion status and site on the soil variables.

	Wilks' Lambda	<i>F</i> -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

#### 2. 4.2 Effects of invasion status on soil variables

The invasion status had statistically significant effects on P, K, N, CEC, total cations, acid saturation and pH (p < 0.05, Table 2.2) whereas marginal significant differences were detected for Mg and Zn (p < 0.1, Table 2.2). The P was significantly higher in the invaded samples compared to soils in both cleared and uninvaded areas. In addition, K, CEC, N, Zn and total cations were highest (p < 0.05) 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 significantly high in the uninvaded areas while acid saturation was highest in the cleared (Table 2.2). 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 2.2. Effect of invasion status on soil variables at 10 - 20 cm depths. Mean (N = 24) ± standard deviation soil properties were 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	<i>F</i> -	p-value
					statistics	
Bulk density	$1.2 \pm 0.1$	$1.9 \pm 2.3$	$1.9 \pm 2.5$	2	1.3	0.27*
(g mL <sup>-1</sup> )						
P (mg L <sup>-1</sup> )	$11.5 \pm 9^{a}$	$\textbf{22.8} \pm \textbf{36.4}^{\text{b}}$	7.1±5.4 <sup>ac</sup>	2	4.2	0.022
K (mg L <sup>-1</sup> )	95.7±54.7 <sup>a</sup>	$132.5 \pm 64.3$ <sup>b</sup>	$124.2 \pm 61^{ab}$	2	3.5	0.038
Ca (mg L <sup>-1</sup> )	328±188.6	$314\pm261.9$	$376.46 \pm 156.4$	2	0.8	0.45*
Mg (mg L <sup>-1</sup> )	29.4± 37.3 <sup>(a)</sup>	$49.8 \pm 65.6^{\ (b)}$	$51.7 \pm 35$ <sup>(b)</sup>	2	2.7	0.075
CEC (cmol	$3.5 \pm 1.1^{a}$	$3.7 \pm 1.4^{ab}$	$2.5 \pm 0.1$ <sup>c</sup>	2	13.2	<0.00
L <sup>-1</sup> )						1
Total cations	5.6±1.4 <sup>a</sup>	6±1.2 <sup>ab</sup>	5.1±1.1 °	2	6.6	0.003
(cmol L <sup>-1</sup> )						
Acid	$63.9 \pm 18.7$ <sup>a</sup>	$63.3 \pm 23.8$ <sup>ab</sup>	48.9±15.6 °	2	7.1	0.002
saturation						
(%)						
pH (KCl)	$3.72 \pm 0.24$ <sup>a</sup>	$3.7 \pm 0.2^{\ \mathbf{b}}$	$3.9 \pm 0.2^{\text{ ac}}$	2	13.2	<0.00
						1
Zn (mg L <sup>-1</sup> )	$1.6 \pm 1.3^{a}$	3.6±6.3 <sup>b</sup>	$3.2 \pm 4.92$ <sup>b</sup>	2	2.7	0.074
N (kg ha <sup>-1</sup> )	$\textbf{0.18} \pm \textbf{0.04}^{a}$	$0.21\pm0.05~^{ab}$	$0.18 \pm 0.04$ ac	2	6.4	0.003

According to ANOVA, only K, Ca, N and total cations were statistically different between the 10 and 20 cm depths (p < 0.05, Table 2.3). With respect to these variables higher values were observed at the 10 cm depth compared to the 20 cm one (Table 2.4).

	Cleared		Invaded		uninvade	d	<i>F</i> -	p-value
Depth	10 <b>c</b> m	20cm	10 <b>c</b> m	20cm	10 <b>c</b> m	20cm	value	
Bulk	1.2 ±	$1.2 \pm 0.6$	2.6 ±	1.2 ±	1.9	1.9	1	0.33
density (g	0.6		0.6	0.6	±0.6	±0.6	2.5	0.12
mL <sup>-1</sup> )								
P (mg L <sup>-1</sup> )	$16 \pm 6$	$7.1 \pm 6$	28.±6	$17 \pm 6$	$10 \pm 6$	$5\pm 6$	3	0.12
K (mg L <sup>-1</sup> )	110 ±	82 ± 16	164 ±	101	149	$100 \pm$	<b>12.</b> 7	< 0.01
	16		16	±16	±16	16		
Ca (mg L <sup>-</sup>	361±59	$295\pm59$	399 ±	229 ±	410 ±	$343 \pm$	4.5	0.04
<sup>1</sup> )			59	59	59	59		
Mg (mg L <sup>-</sup>	$31 \pm 14$	$28 \pm 14$	$43 \pm 14$	$57 \pm 14$	$60 \pm 14$	44 ±	0.04	0.85
<sup>1</sup> )						14		
CEC	3.57±0.	$3\pm0.3$	$4 \pm 0.3$	$4 \pm 0.3$	$2 \pm 0.3$	3 ±	0.08	0.79
(cmol L <sup>-1</sup> )	3					0.3		
Total	$6 \pm 0.3$	$5\pm0.3$	$7\pm0.3$	$5 \pm 0.3$	$5\pm0.34$	5 ±	6.6	0.01
cations						0.3		
(cmol L <sup>-1</sup> )								
Acid	$60 \pm 6$	68 ± 6	$60 \pm 6$	$67 \pm 6$	$45 \pm 6$	$53\pm 6$	2.6	0.11
saturation								
(%)								
pH (KCl)	$4 \pm 0.1$	$4\pm0.1$	$4 \pm 0.1$	$4 \pm 0.1$	.4 ±0.1	4 ±.	0.22	0.64
						0.1		
Zn (mg L-	$2 \pm 1.4$	$2 \pm 1.4$	5±.1.4	$3 \pm 1.4$	$4 \pm 1.4$	2 ±	1.6	0.2
<sup>1</sup> )						1.4		
N (kg ha <sup>-1</sup> )	$0.21\pm$	0.16	$0.24$ $\pm$	0.18±0	$0.2 \pm$	$0.2 \pm$	22.6	< 0.01
	0.01	±.0.01	0.01	0.01	0.01	0.01		

Table 2.5. Mean ± standard error of selected soil variables at two depths (10 and 20 cm) across the study sites. Bolded text indicates significant differences between the two depths.

# 2.4.3 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 difference (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).

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

Table 2.6. 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).

# 2.4.4 Interactive effects of site and invasion status

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

Soil variable	df	F-statistic	p-value
Bulk density (g mL <sup>-1</sup> )	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 <sup>-1</sup> )	6	3.5	0.01
$Mg (mg L^{-1})$	6	3.5	0.01
CEC (cmol L <sup>-1</sup> )	6	7.8	<0.001
Total cations (c mol L <sup>-1</sup> )	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 <sup>-1</sup> )	6	6.121	<0.001

Table 2.7. Interactive effects of site and invasion status on selected soil variables.

#### 2.4.5 Principal components analysis

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 (Appendix A, Table A.1). 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), Appendix A, Table A.2). The first rotated component had high loadings for K, Ca, Mg, total cations and acid saturation (Appendix A, Table A.3). 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 (Appendix A, Table A.4). In order to further illuminate on the effects of invasion status on the selected soil variables a biplot is presented (Fig. 2.2). 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 (Fig. 2.2). 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 (Fig. 2.2).



Figure 2.2. 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).

# 2.4.6 Vegetation cover and aboveground grass biomass in cleared areas

In cleared areas, mean surface cover was 66, 24 and 7% for grass, bare surface and forbs respectively. The remaining 5% was accounted for by tree, rock, wood and stump cover (Fig. 2.3).



Figure 2.3. Surface cover in cleared areas (N = 21 line transects, 1 = grass, 2 = soil, 3 = shrub, 4 = wood, 5 = forbs, 6 = stump, 7 = tree and 8 = rock).

#### 2.4.7 Line transect calibration in the study area

The regression line between dry matter and canopy cover was forced through zero because where there is no cover there is no biomass. The regression slope between grass canopy cover and ANPP was 88.5 and  $R^2$  of 0.96 (p < 0.001, Fig 2.4).



Figure 2.4. The relationship between ANPP and grass cover derived from one hundred and five  $0.2 \text{ m}^2$  sub-plots alongside each of the twenty-one 100 m line transects.

# 2.4.8 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 (Ndovel, 2014) in the Eastern Cape was also analysed to compare with results from the present study. The relationships between ANPP and the disc settling height were highly significant (p < 0.001, Fig. 2.5 and Table 2.6).

Table 2.8. Statistics of the linear regression between ANPP and disc settling height in the study area

Site	df	F	Standard error of estimate
Commercial	53	126.6	12.73
Communal	89	173.3	15.12
Combined	143	231.7	15.42
Ndovela (2014)*	43	37.3	7.9

\*Data from an un-grazed burning trial (Dohne sour veld grassland) at Dohne Agricultural Development Institute, Eastern Cape, South Africa.



Figure 2.5. Calibrating the disc pasture meter under different land tenure arrangements in the southern Drakensberg highland grassland of the north Eastern Cape, South Africa. a) Commercial, b) communal, c) combined commercial and communal and d) un-grazed burning trial at the Dohne Agricultural Development Institute (Ndovela, 2014) with 95% confidence limits.

#### 2.4.9 Predicted ANPP across sites

Mean canopy cover for respective sites and the regression equation developed from the line intercept method were used to predict ANPP in each of the study sites. 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. These averages were used to estimate ANPP across sites using the equation developed from the application of the line intercept method in this chapter (Fig. 2.3). Based on the average combined canopy cover across the study sites (Fig. 2.3), 290 g m<sup>-2</sup> yr<sup>-1</sup> of ANPP was predicted in areas cleared of *A. mearnsii* in the north Eastern Cape (Table 2.7). 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 ANPP data (commercial and communal area) and the Ndovela (2014) study regressions (Table 2.6, Fig. 2.5), ANPP for each site was predicted (Table 2.6). Tukey's HSD revealed that grass ANPP for each of the three sites was statistically different (p < 0.01). Predicted ANPP was 10 and 8% higher in S50E compared to T12A and T35B respectively. Based on the average DPM settling height across the sites, ANPP of 313 g m<sup>-2</sup> yr<sup>-1</sup> was predicted for areas cleared of A. mearnsii in the north Eastern Cape. A comparison of the ANPP predictions from the present study with other similar studies across a latitudinal and rainfall gradient is presented (Table 2.7). Higher predicted grass ANPP for South African sites coincided with areas that received higher mean annual rainfall based on gridded data (Schulze, 1997) as shown in Table 2.7. However, sites cleared of IAPs at the lower end of the rainfall gradient like T12A yielded similar or more ANPP than some higher rainfall sites of O'Connor (2008) and Everson & Everson (2016) studies (Table 2.7). As was the case with the line intercept method, Tukey's HSD indicated that predicted ANPP of each sites were statistically different (p < 0.01). The DPM predicted ANPP at T12A was 17% and 22% less than that of S50E and T35B respectively. In sharp contrast with the line intercept data, grass ANPP 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 ANPP compared to the DPM method (Table 2.7). Overall, DPM predicted 8% more ANPP than and line intercept method (Table 2.7).

Site	Location	*MAR	**DPM	Line intercept
		(mm)	<sup>++</sup> ANPP g <sup>+</sup> DM m <sup>-2</sup> yr <sup>-</sup>	<sup>++</sup> ANPP g <sup>+</sup> DM m <sup>-2</sup> yr <sup>-1</sup>
			1	
S50E	31°40'41 S	772	324	314
	27°35'12 E			
T12A	31°31'25S	655	270	283
	27°45'27E			
T35B	31°04'05 S	786	348	288
	28°17'34E			
Combined (S50E,	31°04-41 S	737.7	314	290
T12A & T35B)	27°3528°17 E			
Danckwerts &	32°42'05 S	409	252	N/A
Trollope (1980,	26°27'18E			
grazed trial)				
O'Connor (2008,	29°45'01 S	893	292	N/A
grazed commercial	29°33'07E			
and communal	29°49'01 S	862	244	N/A
rangelands)	29°37'57E			
Everson &	28°56'17 S	880	471	N/A
Everson (2016,	29°157'41E			
biennial burnt)				
Ndovela (2014,	32°32'28 S	680	254	N/A
un-grazed burning	27°27'47E			
trial)				

Table 2.9. Predicted annual dry matter production (kg DM m<sup>-2</sup> yr<sup>-1</sup>) using canopy cover and DPM method.

\*Mean annual rainfall, <sup>++</sup>Aboveground net primary productivity, \*\*Disk pasture meter and <sup>+</sup>Dry matter.

# **2.5 Discussion**

# 2.5.1 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 reduced 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 & 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 soil to retain and exchange nutrients. The ability of soil to attract positive cations (for example, Ca<sup>2+</sup>, Mg<sup>2+</sup>, Na<sup>+</sup> and K<sup>+</sup>) 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 & Lorandi, 2012). Such soils require less lime to correct the pH than those with CEC values greater than 6 cmol L<sup>-1</sup> (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 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 (Forrester et al., 2007; Lazzaro et al., 2014; Moyo & Fatunbi, 2010; Tye & Drake, 2012). 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.

#### 2.5.2 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 socio-ecological systems described in this work should be informed by an appreciation of local soil properties. Admittedly, impacts of acacia invasions are well documented (for example, Moyo & 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*. An 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 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. The PCA revealed a major environmental gradient along the axes as there were pronounced differences in adjacent sampling points. 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.

## 2.5.3 Response of ANPP after removal of IAPs

Herbage production is intricately intertwined with the quality of the soil and this has implications on livestock production. For example, physical, chemical and biological soil characteristics influence biomass production and nutrient recycling (Costantini et al. 2016). The regression equations developed were similar to other studies (for example, Flombaum & Sala, 2007; Ndovela, 2014). With respect to the DPM, the data rejected the widely-held perception that biomass production on commercial land differs substantially from communal areas (O'Oconnor, 2008; Palmer & Bennet, 2013) since ANPP from the two areas were similar. There was good agreement between the line intercept and DPM approaches, thus validating ANPP 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 ANPP predicted across sites were similar to other estimates, albeit, in natural grasslands uninvaded by IAPs. In the Eastern Cape, Danckwerts & Trollope (1980) found ANPP values ranging from 213 to 304 g m<sup>-2</sup> yr<sup>-1</sup> of ANPP in *Themeda, Digitaria/ Sporobolous* spp. dominated landscapes. O'Connor (2008) found ANPP values of 292 and 244 gm<sup>-2</sup> yr<sup>-1</sup> in commercial and communal rangelands of the southern Drakensberg area. Everson & Everson (2016) using longterm data estimated ANPP values ranging from 190 g m<sup>-2</sup> yr<sup>-1</sup> for montane grassland exposed to annual winter burning to 471 g m<sup>-2</sup> yr<sup>-1</sup> for grasslands exposed to two yearly burning. Further, Everson & Everson (2016) reported that very early studies in South Africa estimated ANPP from 63 g m<sup>-2</sup> yr<sup>-1</sup> for grasslands receiving 500 mm mean annual rainfall, to 390 g m<sup>-2</sup> yr<sup>-1</sup> 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. Suffice to note that *A. mearnsii* canopy undermined grass production in the present study area (Gwate et al., 2016).

The estimated ANPP was also influenced by precipitation. It is well established that ANPP of grasslands is strongly coupled to precipitation (Sala et al., 1988). Results of this study revealed the effect of rainfall gradient on ANPP, with high rainfall areas coinciding with higher ANPP compared to lower rainfall areas. However, sites cleared of IAP at the lower end of the rainfall gradient were as productive and even better than some higher rainfall sites of the O'Connor (2008) and Everson & 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 & Collins, 2014; Everson & Everson, 2016). For the sites in the present study, the high predicted ANPP 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 & Attiwill, 2003; Forrester et al., 2005; Forrester et al., 2007; Boudiaf et al., 2013; Lazzaro et al., 2014).

#### 2.6 Conclusion

The principal aim of the study was to determine the effects of *A. mearnsii* on soil chemical properties and grass production in rangelands. By analysing selected soil variables, the study demonstrated that these variables were influenced by *A. mearnsii* invasion. *Acacia mearnsii* grossly altered the abiotic components of the soil. Statistically significant differences were found among cleared, invaded and uninvaded grasslands. The PCA 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 complex socio-ecological system should aim to maximize the soil fertility benefits defined by the observed principal components from the present study. Above all, when planning rehabilitation, it is crucial to understand background local soil characteristics and how they could interact with effects of invasion or clearance. The study has also developed regression equations to predict ANPP using non-

destructive methods. Line intercept and the DPM were used in predicting ANPP and there was agreement between these two independent methods as well as other published studies, which validates the results. These equations are easy to use and may enable farmers to estimate forage availability and fuel loads using non-destructive methods in grasslands cleared of *A. mearnsii*. The calibrations in this work took place in a context where the invaded sites were simply clear felled followed by no other management intervention. Hence, results suggest that background rangeland production can still be attained if clearing is not accompanied by active soil management interventions, indicating that recovery thresholds have not been surpassed.

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# CHAPTER 3: EXPLORING THE INVASION OF RANGELANDS BY ACACIA MEARNSII (BLACK WATTLE): BIOPHYSICAL CHARACTERISTICS AND MANAGEMENT IMPLICATIONS

This chapter has been published.

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OG conducted all of the field campaigns, analysed the data and wrote the text in this chapter.

## 3.1 Abstract

Australian Acacias have spread to many parts of the world. In South Africa, species such as *A. mearnsii* and *A. dealbata* are invasive. Consequently, more effort has focused on their clearing. In a context of increasing clearing costs, it is crucial to develop innovative ways of managing invasions. Our aim was to understand the biophysical properties of *A. mearnsii* in grasslands as they relate to grass production and to explore management implications. Aboveground biomass (AGB) of *A. mearnsii* was determined using a published allometric equation in invaded grasslands of the north Eastern Cape, South Africa. The relationships among the *A. mearnsii* leaf area index (LAI), Normalized Difference Vegetation Index (NDVI) and AGB were investigated. The influence of *A. mearnsii* LAI and terrain slope on grass cover was also investigated. Strong linear relationships between NDVI, LAI and AGB were developed. *Acacia mearnsii* canopy adversely impacted grass production more than terrain slope (p < 0.05) and when LAI approached 2.1, grass cover dropped to below 10% in infested areas. Reducing *A. mearnsii* canopy could promote grass production while encouraging carbon sequestration. Given the high AGB and clearing costs, it may be prudent to adopt the 'novel ecosystems' approach in managing infested landscapes.

## Keywords: grassland, invasive plants, landscape ecology, rangeland condition

# **3.2 Introduction**

Invasive Alien Plants (IAPs) are a major force for global change as they often alter the structure and functioning of ecosystems. Australian acacias (wattles) have been transported to different parts of the world (mainly between 35° North and 40° South) through various mechanisms such as transfer, diffusion and dispersal (Kull et al. 2011; Le Maitre et al. 2011). They often become invasive in their new environments especially when growing outside plantations. The concomitant mix of carbon and nitrogen fertilization as well as the dynamics in land use affect resource distribution and amplify their invasiveness (Simberloff et al. 2013) and general woody densification reported in grasslands (Wigley et al. 2010; Estell et al. 2012). Therefore, management of the invaded landscape remains a challenge in a context of global environmental changes associated with increasing atmospheric CO<sub>2</sub> concentration.

Globally, most rangelands become dominated by a new combination of plants and animals due to anthropogenic activities forming what has been referred to as 'novel ecosystems' or 'emerging ecosystems' (Hobbs et al. 2014). A 'novel ecosystem' relates to a completely transformed socio-ecological system from its historical baseline due to human activities such that restoration of the original system may not be possible (Hobbs et al. 2009; Morse et al. 2014). An estimated 18x10<sup>4</sup> km<sup>2</sup> of land in South Africa is infested by IAPs (Kotzé et al. 2010) and thus transforming the landscape. In South Africa, grassland comprise about 27.9% of the total area of biomes and is the second largest after the Savanna Biome (Van Wilgen et al. 2012). About 30% of the South African Grassland Biome has been permanently modified (Mucina et al. 2006) and this affects livestock and wildlife production. Invasion by woody plants is one of the pervasive drivers of grassland transformation in South Africa and it influences rangeland production. Although woody encroachment in grasslands means higher storage of carbon, the usefulness of this carbon in providing local ecosystems services is questionable. In areas where the forest markets are efficient, communities could easily sell the problematic IAPs such as Acacia mearnsii (black wattle) as timber to prospective buyers and money used for community development. However, in a context of weak market linkages for A. mearnsii such as in the rural areas of the former Transkei in the north Eastern Cape, the invasion may be even more disadvantageous to local farmers. Communal farmers have indicated a preference for grazing and cultivation rather than stands of A. mearnsii (Adam Perry, University of Fort Hare, pers. comm., 2014).

South Africa is implementing a Payment for Ecosystems Services (PES) programme to clear IAPs. This is done under the auspices of the Working for Water (WfW) programme at an annual cost of approximately US\$100 million (Turpie et al. 2008). The WfW programme is an extended public works programme that began in 1995 to clear land of IAPs since they adversely affect water resources and threaten ecological integrity (Van Wilgen et al. 2012). It also seeks to provide job opportunities, training and economic empowerment (Turpie et al. 2008). IAPs in South Africa are reported to have a very high total incremental water use compared to indigenous vegetation (Clulow et al. 2011) and it is believed that clearing therefore will salvage a significant proportion of water to maintain other ecosystem services (Van Wilgen et al. 2008; Meijninger and Jarmain 2014). To be successful, clearing of IAPs should be followed by effective regeneration of indigenous vegetation cover. From a rangelands production perspective, application of an effective post clearing management regime is required in order to improve the grass cover within the landscape and this can ensure that there is controlled runoff and groundwater recharge. It is envisaged that if more water is salvaged and retention time is increased, then more productive local desirable vegetation is likely to grow particularly if re-vegetation is done (Holmes et al. 2008). From a grazing perspective, this means higher grass production. Increased grass biomass invariably contributes to improving livestock and wildlife production in such areas.

Rangelands provide a number of ecosystem services such as forage production, water supply, habitat, biodiversity, carbon sequestration and recreation amongst others. In order to understand loss or gain of such ecosystem services as a result of *A. mearnsii* infestation in a given area, an appreciation of the magnitude of the infestation is vital. Hence, an investigation into the biophysical attributes of the components of these invaded landscapes related to the leaf area index (LAI), normalised difference vegetation index (NDVI) and aboveground biomass (AGB) could be useful. These vegetation attributes have direct implications on resources use (water, sunlight and minerals) and on the carbon sequestration ability by any given vegetation stand. This in turn influences the ability of an infested rangeland to produce ecosystems services required by local farmers. Therefore, from a rangeland management perspective, it will be prudent to understand how these vegetation attributes influence grass production which is important for local farmers.

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<sub>2</sub> 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 prioritized 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 free-hold 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 WfW. It has been recognised that the implementation of a strategy to deal with IAPs should take place within the broader framework of adaptive management (Van Wilgen et al. 2011; Sayre et al. 2012). This suggests that policies could be implemented experimentally, with a desire to learn and promote continuous improvement in the management of severe problems such as IAPs. The aim of this study was to understand the biophysical properties of *A. mearnsii* in grasslands as they relate to grass production and to explore possible alternative management options. It is envisaged that this understanding could form the basis for future research on management of infested rangelands.

## 3.3 Material and methods

#### 3.3.1 Study area

Three quaternary catchments in the Kei and the Umzimvubu Primary Catchments were selected for the study (Figure 3.1). These were quaternary catchments S50E, T12A and T35B which represent areas where IAPs are a known threat and some clearing by WfW has taken place. Catchments S50E and T12A are located within the Emalahleni and Sakhisizwe Local Municipalities (Chris Hani District Municipality). Catchment S50E supplies the Ncora dam on the Tsomo River. The Ncora dam was completed in 1975 and has a capacity of  $150 \times 10^6 \text{ m}^3$ and a surface area of approximately 1392 ha. The land tenure is exclusively leasehold, with approximately 15 villages occurring in this quaternary catchment. In quaternary catchment T12A there is a history of both leasehold and freehold tenure, although the recent (post-1976) land re-distribution programme has seen the creation of several new leasehold (communal) villages from previous freehold farms. Across both catchments, the main economic activities are livestock production (cattle, sheep, goats and poultry) and rain-fed annual crop production. T35B is a quaternary catchment for the Pot River, a tributary of the Mzimvubu River. The land tenure system within this quaternary is predominantly freehold, with significant commercial forest plantations, dry land cultivation and livestock production off un-improved natural rangeland. Across all the study sites A. mearnsii is clustered in isolated patches  $< 1 \text{km}^2$ .



Figure 3.1. Map of the percentage density of *Acacia mearnsii* (black wattle) and three quaternary study sites (S50E, T12A and T35B) in the Eastern Cape (adapted from Kotze et al. 2010).

## 3.3.2 Methods

## Estimation of A. mearnsii density

Using Google Earth images, a total of nine sites that represented dense A. mearnsii stands were identified. With respect to quaternary catchments S50E and T12A, five and three sites respectively were identified. In quaternary catchment T35B there was only one patch of land that was densely invaded. Acacia mearnsii stand density was measured using the point-centredquarter (PCQ) method (Cottam and Curtis 1956; Bonham 1989). At each site, data were collected from three replicated points, making a total of 27 points across sites. Density sampling points were separated by a distance of 40 m and the replication of samples ensured that the derived densities were sufficient and representative of the stand. In general distance methods help to reveal connectedness or pattern within plant communities (Fidelibus and MacAller 1993). PCQ is a robust method that provides more data per sampling point than other distance methods (Cottam and Curtis 1956). Taking into consideration variations in stem characteristics across the invaded patches, three size classes based on the Diameter at Breast Height (DBH: 1-5 cm, > 5-10 cm and > 10-15 cm) were defined to determine the density of each class at selected points. Distances to the nearest individuals in each quadrat and in each size class were measured using a laser distance measure (Leica DISTO<sup>TM</sup> X 310). Only trees that were within 10 m of the sampling point were considered since beyond this, the laser beam

was not visible in the *A. mearnsii* forest. The replication of sample points ensured that variation in tree density across the landscape was captured.

#### Above-ground standing biomass estimation

Allometric equations are useful methods for determining biomass in a quick and nondestructive manner (Flombaum and Sala 2007; Kuyah et al. 2012; Chave et al. 2014), and have often been developed for biomass estimation in plantations. The possibility of developing allometric equations for trees growing outside the plantations has also been demonstrated (Kuyah et al. 2012; Paul et al. 2013; Chave et al. 2014). An allometric equation for predicting *A. mearnsii* biomass using DBH, developed by Paul et al. (2013) for the mesic (rainfall > 300 mm) southern and eastern Australia, was applied in this study to predict biomass per hectare. The equation uses a power function which has a linear equivalent form:

$$\ln(\mathbf{y}) = a' + \mathbf{b} * \ln(\mathbf{x}) + e'$$

[1]

where, y is the aboveground biomass (AGB) kg tree<sup>-1</sup>, expressed on a dry weight basis and x is the stem diameter in centimetres (cm), a' is the intercept and b is the scaling allometric exponent and e' is the error term. The adopted equation is as follows:

 $\ln(y) = -2.02 + 2.46 * \ln(x) + 0.157$  [2]

# Grass cover, LAI and NDVI measurements

To evaluate local factors determining grass cover, sampling was informed by the land systems approach (Van der Merwe et al. 2015). Land systems are natural areas with a recurring pattern of topography, soils, vegetation, drainage and other physical features in relatively uniform climatic regimes. Therefore, land systems and their facets do not occur randomly but are systematically linked by geomorphologic processes, origin and water movement (Van der Merwe et al. 2015). In addition, land systems are not confined to one environmental factor but cover a whole range of the physical environment to the extent that it influences environmental potential. This broader outlook is necessary to better understand the influence of physical factors affecting grass production in areas infested by *A. mearnsii* in order to develop appropriate interventions. Based on the land systems approach, it is assumed that areas within a similar gradient should have more or less similar vegetation cover. Hence, 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 hypothesized that a particular black wattle canopy LAI and terrain slope combination militates grass production.

#### LAI measurements

Woody canopy LAI (usually dominated by *A. mearnsii*) was determined using an AccuPAR ceptometer model LP-80 PAR/LAI (Decagon Devices Inc., Pullman, Washington USA). The ceptometer determines the fraction of photosynthetically active radiation (fPAR) intercepted by the canopy, and uses a gap analysis algorithm to determine LAI (Butterfield and Malmstrom 2009). At each sampling point repeated (> 5) recordings of LAI were performed to derive the mean value since each reading gives a slightly different result due to variations in solar incident radiation recorded by the instrument.

## Normalized difference vegetation index (NDVI)

Landsat 8 Climate Data Record (CDR) Surface Reflectance data product images for the area were acquired for a scene closest to the date of sampling events (scene ID LC81690822015172LGN00) and an NDVI was produced from bands 4 and 5 using ArcGIS version® 10.2 (ESRI, USA). NDVI values for pixels that coincided with sites, where stand density was assessed, were then extracted. Since the data varied and had no fixed values, Standard Major Axis (SMA) regression was performed to determine the relationship between NDVI and AGB at the 0.05 significance level in R software environment (R version 3.1.3). SMA tries to minimize the squared errors in both the *x* and the *y* values (Warton et al. 2006).

## Grass cover and slope measurements

Grass cover was estimated at the point where LAI and slope were measured. At each sampling site, grass cover was determined below the *A. mearnsii* canopy using a 1.0 m x 0.2 m quadrat (Bonham 1989; Flombaum and Sala 2007). The quadrat was thrown three times around each sampling point and percentage cover was an ocular estimate based on the area covered by grass in order to derive an average percentage value. Three throws were found adequate during our pre-testing since the average estimated percentage cover did not change significantly beyond three throws on the small (area wise) sampling point. Ocular approaches using small quadrats improve the accuracy of cover estimates and are a quick way of sampling (Winkworth et al. 1962). The slope was measured using a laser distance measure (Leica DISTO<sup>TM</sup> X 310) in degrees. Subsequently, linear regressions were prepared to predict grass cover from slope and LAI individually and also from a combination of the two in order to determine critical

thresholds required for viable grass production. In order to investigate critical levels for canopy LAI required to sustain viable grass cover, a generalized linear model using the logarithmic link function was fitted to the data.

# 3.4 Results

## 3.4.1 Estimated A. mearnsii density

Average stem density was 27.108 x  $10^3$  stems ha<sup>-1</sup> across the landscape. Diameter at Breast Height (DBH) class 1(1-5 cm) dominated the landscape and contributed 75% to mean density followed by class 2 (> 5-10 cm, 18%) and lastly class 3 (> 10-15 cm, 7%). Figure 3.2 shows the distribution of *A. mearnsii* density per class in the landscape. Absolute total stand density ranged from 17.38 x  $10^2$  to 13.223 x  $10^4$  stems ha<sup>-1</sup>. DBH class 1 density was significantly different from the other two classes (p < 0.05) while classes 2 and 3 were not significantly different.



Figure 3.2. Variation in stem density for *Acacia mearnsii* in each Diameter at Breast Height (DBH) class. 1 = DBH class 1 (1-5 cm), 2 = DHB class 2 (> 5-10 cm) and 3 = DBH class 3 (> 10-15 cm). Letters shared in common between or among the categories indicate no significant differences.

## 3.4.2 Estimated A. mearnsii standing biomass

Mean AGB was estimated at 279 tonnes ha<sup>-1</sup> with the biggest contributor to this biomass being DBH class 3. The proportion of DBH classes 1, 2 and 3 to total AGB was 11, 37 and 52% respectively. For DBH class 1, the highest estimated AGB was 196 tonnes ha<sup>-1</sup> and the lowest

was about 1.7 tonnes ha<sup>-1</sup> (Figure 3.3). With respect to DBH class 2, AGB ranged from 6 to 450 tonnes ha<sup>-1</sup>. The highest standing biomass in DBH class 3 was 612 tonnes ha<sup>-1</sup> while the lowest was 14 tonnes ha<sup>-1</sup>. Predicted AGB differed significantly across the three DBH classes (p < 0.05, Figure 3.3). Absolute total stand biomass ranged from 26 to 866 tonnes ha<sup>-1</sup> across sites.



Figure 3.3. Variation in Aboveground biomass (AGB) for *Acacia mearnsii* in each Diameter at Breast Height (DBH) class 1 = DBH class 1(1-5 cm), 2 = DHB class 2 (> 5-10 cm) and 3 = DBH class 3 (> 10-15 cm). Letters shared in common between or among the categories indicate no significant differences.

## 3.4.3 Relationship between standing biomass, LAI and NDVI

The relationship between NDVI and total AGB was significant (p < 0.05) with NDVI explaining 70% of total variation in AGB ( $R^2 = 0.71$ , Figure 3.4). There was no autocorrelation between adjacent residuals as shown by a Durbin-Watson statistic of 2 and as such the null hypothesis of non-auto correlated errors was accepted. In general, Durbin-Watson statistic values of between 1.5 and 2.5 mean that there is no autocorrelation in the sample while values approaching zero (0) indicate positive autocorrelation and values toward 4 indicate negative autocorrelation.



Figure 3.4. The relationship between Normalized Difference Vegetation (NDVI) and aboveground biomass (AGB) for *Acacia mearnsii* with 95% confidence limit across the landscape.

LAI and NDVI had a strong linear relationship in this study ( $R^2 = 0.73$ , Durbin-Watson statistic = 2.2, Figure 3.5).



Figure 3.5. The relationship between Normalized Difference Vegetation (NDVI) and AccuPAR ceptometer Leaf Area Index (LAI) of *Acacia mearnsii* with 95% confidence limit across the landscape.

#### 3.4.4 LAI thresholds for grass production

The A. mearnsii LAI recorded ranged from 0.14 to 5.12. Terrain slope ranged from 3.2° to 26.1° indicating a very wide environmental gradient where sampling was conducted. Acacia mearnsii LAI and grass cover had a significant relationship (p < 0.05) although LAI explained only about 38% of the variation in the grass cover ( $R^2 = 0.4$ ). Figure 6 shows a grass cover against LAI plot which gives insights into the LAI values that have to be maintained to allow viable grass production. A generalized 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% (Figure 3.6). 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).



Figure 3.6. Relationship between *Acacia mearnsii* Leaf Area Index (LAI) and grass cover percentage across the landscape.

## **3.5 Discussion**

## 3.5.1 Density and standing biomass

*Acacia mearnsii* is well established in the study area as evidenced by the presence of different cohorts of varying size classes. Despite clearing by the WfW programme, and use by the local communities for house construction and wood fuel amongst other uses, the densification of invasion continues. This is also evidenced by very high variability in density and AGB in different DBH cohorts across the sites, suggesting that *A. mearnsii* distribution was highly inconsistent, probably due to the varying intensity of use, clearing and historical planting as woodlots. DBH class 3 contributed a significantly larger proportion of AGB than each of the other two classes and this was consistent with results from elsewhere (Sist et al. 2014; Kuyah and Rosenstock 2015). Higher density for small stems confirms that *A. mearnsii* densification is taking place in the study sites.

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.

In the selected quaternary catchments, particularly S50E and T12A, *A. mearnsii* was freely available as a common property resource but there were no communal institutions for its management. Many negative aspects of *A. mearnsii* related to water use and biodiversity loss have been reported (for example, Marais and Wannenburgh 2008; Turpie et al. 2008; Van Wilgen et al. 2008; Meijninger and Jarmain 2014) and dense stands are reportedly a haven for criminals (Magwalana community members pers. comm., 2014) with community members). On the other hand, *A. mearnsii* is also crucial for fuel and supports livelihoods (Kull et al. 2011; Van Wilgen et al. 2011; Simberloff et al. 2013). Within the broader context of global change, it is also crucial as a carbon sink. Extensive livestock and crop farming are major livelihood activities in the study sites. Therefore, heavy infestation leads to a concomitant loss of land available for key livelihood activities. With the density of infestations reported in this paper, it is not surprising that there has been little progress in reducing the invaded area in the study

catchments. In addition, there has seldom been any follow-up after clearing. *Acacia mearnsii* clearing efforts have revolved around clear felling the entire stand and leaving most of the residues to rot *in situ*. Although Holmes et al. (2008) recommended clear fell and removal of wood as an effective approach, with the very high densities reported here, it may not be a viable long term policy. McConnachie et al. (2012) reported that despite huge financial expenditure, the current IAPs control efforts in South Africa were insufficient to stop their spread. For example, Van Wilgen et al. (2012) found that since 1995 only 8% of the estimated *A. mearnsii* invaded land has been treated in the Savanna and Grassland Biomes.

The AGB reported in this paper may be economically viable if communities are linked to the market to sell *A. mearnsii*. This would mean identifying prospective buyers of the resource in the forestry and chipboard industry to do business with the communities. The local baseline data generated in this paper, 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.

# 3.5.2 LAI-NDVI and standing biomass relationships

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 ( $\sum$ 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.

# 3.5.3 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. It is well established that local physical landscape factors such as nutrients, aspect, runoff and run-on dynamics are critical in modulating grass production. Therefore, sampling across a very wide environmental gradient ensured that the influence of these factors did not colour our results. From the sampling conducted (terrain slope ranging from 3.2° to 26.1°), 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<sub>4</sub> 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* amongst 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 socioecological 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 et al. 2009; Hobbs et al. 2014). Therefore, it is consistent with the adaptive management approach for intractable problems and may be worth embracing with respect to management of IAPs.

Literature seems to imply that some IAPs will not be eradicated in the foreseeable future owing to economic costs attached to treatment efforts and environmental factors modulating their propagation (Holmes et al. 2008; Le Maitre et al. 2011; Van Wilgen et al. 2011). While biological and chemical control maybe promising, uncertainties on their ecosystem impacts deter their widespread adoption. The primary motivation for clearing IAPs in South Africa is to salvage water, restore structure and functioning of natural ecosystems and to increase the productivity of the land (Holmes et al. 2008). Given the density reported in this paper and the pace of clearing, these objectives have remained largely elusive in our study sites. Therefore, it can be submitted that preoccupation with restoring ecosystems to an earlier state may not be pragmatic for South Africa, particularly in the rangelands. As such, it becomes prudent to rethink about such biological invasions or exploit their beneficial services and adopt ecological thinning as an adaptive management strategy.

#### 3.6 Conclusion

*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 socioecological 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.

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# CHAPTER 4: WATER VAPOUR AND ENERGY FLUXES OVER THE ALBANY THICKET OF THE EASTERN CAPE, SOUTH AFRICA

This chapter has been published in a peer-reviewed conference proceedings.

**Gwate, O.,** Mantel S. K., Palmer, A. R., Gibson, L. A. (2016). Measuring evapotranspiration using an eddy covariance system over a subtropical thicket of the Eastern Cape, South Africa. In *SPIE Remote Sensing for Agriculture, Ecosystems, and Hydrology XVIII* (Vol. 9998, p. 99980S). <u>http://doi.org/10.1117/12.2245426</u>

OG was part of a small team (OG, ARP and SKM) that installed the eddy covariance system in the Albany Thicket. OG assisted with the in-field installation, calculated system parameters for use in the EddyPro® software, analysed all the water and energy fluxes using EddyPro® and wrote the manuscript.

# 4.1 Abstract

A better understanding of factors modulating water and energy fluxes partitioning over vegetated surfaces is important in a context of global environmental changes and associated feedbacks to ecosystems. This study reports annual eddy covariance (EC) measurement of water vapour and energy fluxes over the Albany Thicket (AT) dominated by the facultative Crassulacean Acid Metabolism (CAM) photosynthesising Portulacaria afra in the Eastern Cape, South Africa. P. afra has recently received renewed interest in South Africa through widespread environmental plantings as it is believed to be a net carbon sink. Environmental constraints to ET were assessed by examining the response of ET to biotic and abiotic factors. Bulk parameters in the form of surface conductance  $(G_s)$ , Priestley-Taylor coefficient (¥) and the decoupling factor ( $\Omega$ ) were used to evaluate the integrated impact of biophysical factors on energy and water vapour fluxes partitioning. On an annual scale, 62% of net radiation  $(R_n)$ was consumed by sensible heat flux (H) and the  $\frac{1}{4}$  was  $\frac{1}{4}$  indicating that the area was water limited. The low  $\Omega$  (< 0.05) suggested strong connection between the canopy and the boundary layer. Hence, ET was greatly influenced by  $G_s$  and vapour pressure deficit (VPD), indicating plant adaptive capacity to control water use. This suggests the need for more environmental plantings of vegetation with high water use efficiency like P. afra in a context of water scarcity in order to circumvent increasing atmospheric CO<sub>2</sub>.

*Keywords:* Albany Thicket biome, data quality assessment, eddy covariance system, EddyPro software, energy fluxes, evapotranspiration

#### **4.2 Introduction**

Evapotranspiration (ET) or latent heat flux (LE) is the combined loss of water vapour from plants and from surfaces (Allen et al., 1998). Energy is required to break the strong bonds that hold water molecules together as a liquid and when those bonds break, the individual water molecules may enter the surrounding atmosphere as vapour (Fisher et al., 2011). However, there has to be sufficient wind and favourable vapour pressure deficit (VPD) to aid the transfer of the molecules from the water source to the atmosphere. It has been established that globally over two-thirds of the total precipitation over the continents is returned to the atmosphere as evapotranspiration, making it the largest single component of the terrestrial hydrological cycle after precipitation (Fisher et al., 2005; Fisher et al., 2007; Mu et al., 2011; Hoff et al., 2010; McMahon et al., 2013; Liou & Kar, 2014). In a context of global environmental changes associated with climate change, it becomes important to fully understand dynamics in the

energy and water fluxes over vegetated areas as well as their biophysical controlling factors (Jia et al., 2016).

ET is one of the components of the catchment water budget that can provide key insights into the performance of land cover and land use activities. Consequently, ET controls the largescale distribution of plant communities, primary production and is a vital process linking the hydrological cycle with other biogeochemical processes (Fisher et al., 2011; Ma et al., 2015). Plant water use efficiency (WUE) is the ratio of the rate of net CO<sub>2</sub> assimilation (biomass) to transpiration (Franks et al., 2013). The greater the WUE, the more carbon is fixed per unit water lost, thereby improving the chance of vegetation survival in drier environments or under drought (Fisher et al., 2011). Through links between stomatal conductance, carbon exchange, and WUE, plant ET serves as a regulator of key ecosystem processes. Various Thicket vegetation formations are found in Africa, Madagascar, Asia, Australia and the Americas (Hoare et al., 2006) and such ecoregions are presumed to have very high WUE. The AT biome in South Africa provides an interesting ecosystem to evaluate dynamics in ET. Although the rainfall is low and erratic, the AT of South Africa is associated with high biomass and biodiversity (Hoare et al., 2006). This high tolerance of moisture deficit is linked to high water storage capacity, sclerophylly, CAM photosynthesis and succulence reported in such environments (Mills & Cowling, 2006; Borland et al., 2009; Owen et al., 2016). These characteristics of the biome exacerbate the complexity associated with understanding water and energy flux dynamics in such ecosystems. In South Africa research on the AT biome has mainly focused on carbon sequestration within the broader context of the Clean Development Mechanism, the distribution of particular species and the infiltration and runoff dynamics (Mills & Cowling, 2006; van Luijk, et al., 2013; Becker et al., 2015). Therefore, little attention has been given to water and energy dynamics of the biome and this study will contribute to that direction.

ET is a biophysical process that is strongly controlled by biotic and abiotic factors. For example, plants regulate the opening and closing of their stomata to minimize water loss, while maximizing  $CO_2$  absorption for photosynthesis (Allen et al., 1998). Biotic controls of ET are related to canopy development and ecophysiological properties of plants such as stomata density, stomatal conductance or resistance, phenological stage of the canopy (Li et al., 2007) and rooting dynamics. Abiotic factors are connected to climatic factors such as precipitation, solar radiation, available energy and VPD. The complex interaction between these factors

results in the variation of the pattern and magnitude of ET across environmental gradients. Wang et al. (2012) found that soil moisture/ precipitation was the main driver of ET in a Mongolian steppe and that the relationship between ET and VPD was complex. The same research observed that at high soil moisture, ET was marginally positively coupled to VPD while during periods of high water deficits, a negative correlation prevailed. On the other hand, biotic factors as represented by the LAI have been found to be linearly related to and accounted for much variation in ET (Li et al., 2007; Wang et al., 2012; Liu et al., 2013). Therefore, it will be interesting to evaluate the water and energy fluxes in a physiognomically different biome characterised by AT vegetation to establish if there is any convergence in the behaviour of the land-atmosphere exchanges. However, a better understanding of the integrated impacts of these biophysical parameters is more useful in order to fully account for the partitioning of energy and water vapour fluxes over a given ecosystem. The integrated impacts may be determined by evaluating the bulk parameters such as surface conductance ( $G_s$ , Monteith, 1965), the Priestley-Taylor coefficient (¥, Priestley & Taylor, 1972) and the decoupling factor ( $\Omega$ , Jarvis & McNaughton, 1986). The  $G_s$  is a bulk parameter that modulates the rate of evaporation from bare surfaces and transpiration from the canopy while the  $\Omega$  helps to determine the extent to which the land surface is coupled with the atmosphere. The ¥ relates the ratio of observed latent heat flux (LE) to equilibrium evaporation and helps to discern the sensitivity of ET to water and energy availability (Tong et al., 2016). It is hypothesized that biotic factors related to the behaviour of stomata are likely to play a crucial role in regulating flux exchanges between the land and atmosphere systems in the AT owing to the convergent evolutionary characteristics of the vegetation. Understanding the main factors controlling ET is vital in marginal lands within the broader purview of global change and the need for sustainable management of natural resources such as water.

Land surface ET is one of the least understood and difficult to measure ecohydrological process. Consequently, a number of approaches have been developed to measure ET. Recent developments in technology have reduced uncertainties associated with the measurement of fluxes between the land-atmosphere systems. One of the most dependable and direct methods of measuring ET is the EC method (Baldocchi, 2012; Burba, 2013). The theory of eddy covariance is based on the premise that the fluxes of water vapour and heat within the surface layer are nearly constant with height on relatively flat land, homogenous vegetation and under turbulent conditions. If these basic assumptions are met, the flux of LE and sensible heat (H) can be calculated using the eddy covariance equation (Campbell Scientific, 2013):

$$LE = L_{\nu} \overline{\rho' w'}$$

$$[4.1]$$

$$H = \rho C_p \overline{T'w'} \tag{4.2}$$

where *LE* is the latent heat flux (Wm<sup>-2</sup>),  $L_{\nu}$  is the latent heat of vaporisation (J kg<sup>-1</sup>),  $\rho'$  is the instantaneous deviation of the water density from the mean (kg m<sup>-3</sup>), w' (m s<sup>-1</sup>) is the instantaneous deviation of the vertical wind component from the mean, *H* is sensible heat flux (Wm<sup>-2</sup>),  $\rho$  is the density of air (kg m<sup>-3</sup>),  $C_p$  is heat capacity of air at constant pressure (J kg<sup>-1</sup>K<sup>-1</sup>) and *T'* is the instantaneous deviation of air temperature (K) from the mean.

The theory of eddy covariance is fraught with many assumptions which may not be fulfilled in the real world (Foken et al., 2012; Burba, 2013). In addition, a number of errors such as time delays, frequency response and path averaging errors are bound to occur in the application of the EC system (Burba, 2013). Therefore, it is imperative to implement requisite corrections in order to increase the accuracy in fluxes calculated. This study aims at understanding the landatmosphere energy and water vapour exchanges over the AT vegetation dominated by *P. afra* using an EC system by evaluating biophysical factors. The study is unique in that it is the first to report on energy and water vapour fluxes and an assessment of the impact of integrated biophysical factors on the partitioning of fluxes over the AT biome in South Africa. Sustainable ecosystem management requires improved understanding of water vapour and energy fluxes since it partly influences overall ecosystem productivity.

## 4.3 Material and Methods

## 4.3.1 Experimental site

The AT biome covers about 29 127km<sup>2</sup> (van Wilgen et al., 2012) of the terrestrial biomes of the country and is recognised as a biodiversity hotspot characterised by succulents, deciduous and semi-deciduous woody shrubs and dwarf shrubs, geophytes, annuals and grasses (Hoare et al., 2006). There is a rich diversity of life in terms of the understorey vegetation which comprises dwarf succulent shrubs and forbs, which are essentially *Crassulaceae* and *Aizoaceae*. In addition, perennial grasses such as *Panicum maximum*, *P. deustum* and *Eragrostis* species also form a mosaic of vegetation in the understorey. A suitable patch of land to install the EC station was found at the eZulu Game Reserve, a privately-owned trophy hunting property. The EC site was selected as it contains a large representative example of intact AT dominated by *P.afra*. Estimated mean height of vegetation is 1 m in the theoretical footprint of the EC. The site has been un-grazed by domestic livestock since 1996 and is
currently under light wildlife stocking. Modelled annual pan evaporation is 1963.9 mm while long-term mean annual rainfall is 400 mm (Schulze, 1997). The area has a bimodal rainfall pattern, with mean long-term monthly maxima around October-November and in March. The study site is underlain by sandstone and shale and altitude is 554 m amsl while average slope is 3.6%. The study site is located about 70 km from Grahamstown, Eastern Cape, South Africa (Fig 4.1.).



Figure 4.1. Location of the study area (eZulu Game Reserve).

#### 4.3.2 Instruments

The instruments at the site include an eddy covariance (EC) system and a scientific grade automatic weather station. An Integrated CO<sub>2</sub>/H<sub>2</sub>O Open-Path Gas Analyzer and 3D Sonic Anemometer (IRGASON, Campbell Scientific Inc., Logan, Utah, USA) was installed in October 2015, providing 401 days of continuous observation. An IRGASON is an in-situ, open-path, mid-infrared absorption gas analyser integrated with a three-dimensional sonic anemometer (Campbell Scientific, 2015). The gas analyser provides measurements of absolute densities of carbon dioxide and water vapour, while the sonic anemometer measures orthogonal wind components. The IRGASON is connected to the EC100 electronics, which synchronizes gas and wind data for the calculation of fluxes using the EC method (Campbell Scientific, 2015). The EC100 electronics also use inputs from a temperature thermistor probe and a barometer. The EC100 was then connected to a CR3000 (Campbell Scientific Inc., Logan, Utah, USA) data logger for recording the data.

The IRGASON was installed at a height of 2.65 m above the ground. A shielded (R.M. Young 41303-5A 6-Plate Solar Radiation Shield) temperature and relative humidity probe (HC2S3, Campbell Scientific Inc., Logan, Utah, USA) is installed so that it measures temperature at the same height as the sample volume of the IRGASON in order to measure air that had similar characteristics. Both the IRGASON and the temperature probe are connected to the EC100. Further, a fast response fine wire thermocouple (FW05: 0.0005 in /0.0127 mm, Campbell Scientific Inc., Logan, Utah, USA) is placed between the upper and lower arms of the IRGASON. Other bio-meteorological sensors installed included soil heat flux, volumetric soil water content (SWC), air and soil temperature probes. The soil heat flux (G) is measured using four soil heat flux plates (HFP01, Campbell Scientific Inc., Logan, Utah, USA). The plates were placed at a depth of 80 mm below the soil surface. A system of parallel soil thermocouple probes (TCAV) are installed at depths of 20 and 60 mm to measure soil temperature. A soil thermocouple probe measures temperature at four locations, or junctions, each consisting of a type E thermocouple wire (chromel-constantan) that is enclosed within a stainless steel tube (Campbell Scientific, 2002). The thermocouple works in conjunction with the soil heat flux plate to calculate the heat flux at the surface of the soil. The SWC (CS616, Campbell Scientific Inc., Logan, Utah, USA) was measured in the upper 60 mm of the soil. The installation of the heat flux plates, the soil temperature thermocouples and the water content reflectometer was done following instructions provided by Campbell Scientific (2002). The net radiation  $(R_n)$  is measured using a net radiometer (Kipp & Zonen, Netherlands). Details of instrumentation at the site are presented (Table 4.1).

Bio-meteorological variable	Instrument
Net radiation (W m <sup>-2</sup> )	One net radiometer (NR-lite2, (Kipp &
	Zonen, Netherlands)
Air temperature and Relative humidity (%)	HC2S3 Temperature and relative humidity
	Probe (Campbell Scientific Inc., Logan,
	Utah, USA)
Air temperature (°C)	Fine wire thermocouple (FW05: 0.0005 in
	/0.0127 mm , Campbell Scientific Inc.,
	Logan, Utah, USA)
Soil heat flux (W m <sup>-2</sup> )	4 x soil heat plate (HFP01, Campbell
	Scientific Inc., Logan, Utah, USA)
Soil temperature (°C)	2 x averaging soil thermocouples probe
	(TCAV, Campbell Scientific Inc., Logan,
	Utah, USA)
Volumetric soil water content (m <sup>3</sup> m <sup>-3</sup> )	2 x water content reflectometer (CS616,
	Campbell Scientific Inc., Logan, Utah, USA)
Wind speed (m s <sup>-1</sup> ) and direction (degrees)	IRGASON

Table 4.1. Summary of instruments at the eZulu Game Reserve EC station.

Bio-meteorological probes are also connected to a CR3000 data logger (Campbell Scientific Inc., Logan, Utah, USA) for data recording. Data are saved onto a 2 GB compact flash memory card with the capacity to store up to six weeks of high frequency (10 Hz) data. The EC system is powered by two solar panels (SDT800 - 12V 80W Solar Module) that charge four 100 AmpHour deep cycle batteries (Deltec - SMF 1250 High Cycle).

# 4.3.3 Parameterising bulk surface parameters

In order to have an understanding of the integrated impacts of biophysical factors affecting the partitioning of energy and water vapour fluxes, three model parameters were parameterised, including  $G_s$ ,  $\Omega$  and the  $\Psi$ . The  $G_s$  was determined by inverting the Penman-Monteith equation (Monteith, 1965):

$$G_s = \frac{\gamma LEG_a}{\Delta(R_n - G) + \rho C_p D_a G_a - LE(\Delta + \gamma)} \ge 1000$$
[4.3]

where  $\gamma$  is the psychrometric constant (0.0665 kPa K<sup>-1</sup>), C<sub>p</sub> is the specific heat of air at constant pressure (1013 J kg<sup>-1</sup>K<sup>-1</sup>), *G* is soil heat flux (Wm<sup>-2</sup>),  $\rho$  is the density of air (1.2 kg m<sup>-3</sup>),  $D_a$  is

the air vapour pressure deficit (VPD, kPa),  $\Delta$  is slope relating saturation vapour pressure to temperature (kPa K<sup>-1</sup>),  $G_a$  is the aerodynamic conductance and other terms have been defined.

VPD (Pa) was calculated in EddyPro® 6.0 software and it is given by the difference between actual water vapour pressure and its saturation value:

$$VPD = e_a - e_s \tag{4.4}$$

The actual vapour pressure is given by:

$$e_a = \rho_{h20} \operatorname{R}_{h20} \operatorname{T}_a$$

where  $T_a$  is ambient temperature (K),  $\rho_{h20}$  is ambient water vapour density (kg m<sup>-3</sup>), calculated as:

 $\rho_{h20} = \frac{X_{h20}.M_{h20}}{v_a}$ , where  $X_{h20}$  is mole fraction of water vapour (mol<sup>-1</sup>) and  $v_a$  is ambient air molar volume (m<sup>3</sup> mol<sup>-1</sup>) given by:

 $v_a = \frac{\Re T_a}{P}$ , where P is measured atmospheric pressure

 $R_{h20}$  is the water vapour gas constant and is given by:

$$R_{h20} = \Re/M_{h20} (J \text{ kg}^{-1}\text{K}^{-1})$$
 and

 $M_{h20}$  is molecular weight of dry air ~0.01802 (kg mol<sup>-1</sup>) and  $\Re$  is the universal gas constant ~ 8.314 (J mol<sup>-1</sup> K<sup>-1</sup>)

The saturation vapour pressure was calculated as:

$$e_s = T_a^{-8.2_{\rm \acute{e}}77.345 + 0.0057.T_a - 7235.T_a^{-1}}$$

where  $\acute{e}$  is the base of the exponential function ( $\acute{e} = 2.7182$ )

The  $G_a$  was calculated following Monteith & Unsworth (2013):

$$G_a = \left(\frac{u}{u^{*2}} + 6.2u^{-2/3}\right)^{-1}$$
[4.5]

where u is the mean wind velocity (m s<sup>-1</sup>) and u \* is the friction velocity estimated from the sonic anemometer.

The  $\Omega$  describes the extent to which the saturation deficit at the leaf surface is linked to that of the air outside the leaf boundary layer (Jarvis & McNaughton, 1986). It is a dimensionless factor that takes values in the range 0 to 1, depending on the sizes of  $G_a$  and  $G_s$ . Lower values of the  $\Omega$  indicate that ET is strongly influenced by VPD and  $G_s$  and there is a strong coupling between the boundary layer and the canopy. High  $\Omega$  suggests that ET is essentially sensitive to  $R_n$ . The  $\Omega$  was calculated following Jarvis & McNaughton (1986):

$$\Omega = \frac{\Delta + \gamma}{\Delta + \gamma \left(1 + \frac{G_a}{G_s}\right)}$$
[4.6]

The ¥ relates actual LE to the equilibrium evaporation ( $E_{eq}$ ). The  $E_{eq}$  represents climatological potential evaporation essentially determined by  $R_n$  and it was calculated following Priestley & Taylor (1972):

$$E_{eq} = \frac{\Delta + \gamma}{\Delta + \gamma} (R_n - G)$$
, all terms have been defined. [4.7]

Subsequently, ¥ was calculated as:

$$\Psi = \frac{LE}{E_{eq}}$$
[4.8]

#### 4.3.4 Data analysis

Data were downloaded from the eddy covariance system and sorted for further analysis in EddyPro® 6.0 (https://www.licor.com/env/products/eddy\_covariance/eddypro.html) software. All raw 20 Hz data were firstly processed into half-hourly averages using LoggerNet (4.3) software (Campbell Scientific Inc., Logan, Utah, USA). Post processing included axis rotation for tilt correction which was implemented using double rotation (Wilczak et al., 2001) while the linear detrending method was applied to remove turbulent fluctuations. Time lag compensation was implemented using covariance maximization. Statistical tests for raw data screening, such as spike removal, amplitude resolution, drops outs, absolute limits, discontinuities, time lags, skewness and kurtosis, steadiness of horizontal wind and angle of attack were implemented following Vickers & Mahrt (1997). Random uncertainty estimation was implemented as described by Finkelstein & Sim (2001). The method described by Mauder & Foken (2004) was used to filter out data that failed statistical tests. This method is based on the steady state and integral turbulence characteristic tests and uses the values 0, 1 and 2 as an overall quality flags with fluxes flagged 2 not recommended for use in ET computation. Rejected and missing data were filled using the method of mean diurnal variations (MDV) described by Falge et al. (2001). The EC footprint was estimated using the method of Kljun et al. (2004). The Webb-Pearman-Leuning (WPL) correction was not implemented since the IRGASON internally corrects for density fluctuations.

### **Energy balance**

The shortened energy balance equation is expressed as:

$$R_n = LE + H + G$$

This shortened energy balance equation ignores advection as well as physically and biochemically (photosynthetically) stored heat flux densities in the canopy as they are

[4.9]

considered negligible compared to the other energy balance components (Savage et al., 2004). One of the criteria for flux data quality is energy balance closure. Ideally, the sum of LE and H should be equal to available energy  $(R_n - G)$ . Model II simple linear regression using the Standard Major Axis (SMA) method was used to evaluate the site energy balance by plotting the sum of LE and H (*LE* + *H*) against available energy  $(R_n - G)$ . The SMA was considered suitable since it can handle errors and uncertainties in x and y axis variables (Legendre, 2013). In addition, the closure ratio was assessed and is expressed as follows:

Closure ratio = 
$$\frac{\sum(LE+H)}{\sum(R_n-G)}$$
 [4.10]

SMA was also implemented to investigate the relationship between ET and environmental factors (VPD, LAI, SWC,  $R_n$ ) and available energy ( $R_n - G$ ). In addition, the correlation (r) between bulk parameters and environmental factors such as SWC, VPD and Moderate Resolution Imaging Spectroradiometer (MODIS) leaf area index (LAI, Myneni et al., 2002) was investigated in order to understand the integrated impacts of biophysical factors controlling water vapour and energy fluxes.

#### 4.4 Results

#### 4.4.1 Meteorological conditions

Mean meteorological conditions during the study period (10 October 2015 – 13 November 2016) are presented (Table 4.2).

Table 4.2. Mean  $\pm$  standard deviation of daily meteorological conditions during the measurement period at eZulu Game Reserve station.

Meteorological parameter	Mean $\pm$ SD
Air temperature (°C)	$19.5 \pm 4.7$
Soil temperature (°C)	$24 \pm 6.8$
Relative humidity (%)	$62.24 \pm 12.84$
Vapour pressure deficit (Pa)	$1200.3 \pm 601$
Solar radiation (MJ m <sup>-2</sup> )	$18.3 \pm 7.2$
Wind speed (m s <sup>-1</sup> )	$1.73 \pm 0.75$
Rainfall (mm)	$0.78 \pm 2.5$

The daily minimum and maximum air temperatures were 8.61°C, day of year (DoY 206, 2016) and 31.9°C (DoY 32, 2016) respectively with a coefficient of variation (CV) of 24.1% (Fig. 4.2a). Daily average soil temperature ranged from 10.27 - 39.7°C with a CV of 28.7%. Soil

temperature was consistently higher than air temperature during the growing season (August-April) up to DoY 111, 2016 when the two became more or less equal and this coincided with the onset of the non-growing season (May-July) or (DoY 111 – 205, 2016, Fig. 4.2a). The lowest relative humidity (RH) recorded was 21.13% (DoY 244, 2016) and the maximum was 97.4% (DoY 316, 2016) while the CV was 21% (Fig. 4.2b). The lowest solar radiation recorded was 3.24 (DoY 167) while the highest was 31.30 M J m<sup>-2</sup> (DoY 358, 2015). Average daily solar radiation declined progressively during the cool winter season (DoY 90 – 216, 2016) and the CV was 40% (Fig. 4.2c). A total of 312.4 mm of rainfall was recorded during the 401 days of flux observations and this was less than 22% of the long term modelled mean annual rainfall in the study area. Maximum daily rainfall of 20 mm was recorded on DoY 68, 2016. Rainfall had the highest CV of 324% and wind speed was sufficiently large (0.37 – 4.69 m s<sup>-1</sup>) to drive ET (Fig. 4.2d-e).



Figure 4.2. Daily variation in a) air temperature and soil temperature b) relative humidity, c) solar radiation ( $R_s$ ), d) wind speed and e) rainfall at eZulu during the study period (DoY 283, 2015 - DoY 318, 2016).

# 4.4.2 Flux data quality

The overall flux data availability and quality is presented (Figure 4.3). The majority of missing data (16%) failed the quality control (QC) protocols while 7% was missing due to system/ logging failure. Therefore, the availability of relatively good quality data was at 77%. This percentage availability of data was high enough and adaptable for long-term analysis of evapotranspiration trends.



Figure 4.3. Data availability and quality of the EC data at eZulu station.

In order to ensure that all requisite spectral frequencies were captured, the water flux was plotted against the natural frequency. The plots were done over many different days and at different time periods. The data passed the ogive test (Burba, 2013) on the 30 minute averaging period since the integrated flux approached a constant value at low frequencies (Fig. 4.4).





### 4.4.3 Flux foot print analysis

On average, the source area ranged from 78.4 m in November to 196 m in May when atmospheric stability prevailed (Fig. 4.5a). This means that the average maximum fetch area ranged from 48% to 119% of the theoretical fetch (1: 100) as described by Foken et al. (2012)

given the measurement height of 1.65 m above the canopy. During the months of November and February and January, the source area was shorter compared to the months of October, December, March, April, May up to September. Figure 4.5a shows the variability in source area contributing 90% of the total flux overtime (numbers 1 - 14 represent months from October 2015 to November 2016). The along-wind distance providing the highest (peak) contribution to the turbulent fluxes was 21 m from the tower. Between 28 and 37 m along-wind distance from the tower cumulatively contributed 50% to the turbulent fluxes. On the other hand, between 41 and 65 m away from the tower provided 70% cumulative contribution to the turbulent flux while less than 22 m provided 10 and 30% cumulative of turbulent fluxes, respectively. The prevailing wind (39%) came from between the SW and SE sectors and wind speed from this sector was between 0.1 and 3.1 ms<sup>-1</sup>. Northerly winds were also strong occurring 29% of the time within the NW and NE sectors with wind speed ranging from 0.1 –  $4.1 \text{ ms}^{-1}$  (Fig 4.5b).



Figure 4.5. a) Average flux footprint along-wind distance percentage contribution to 90% to the total flux at eZulu station: numbers 1 - 14 represent months of October 2015 to November 2016. b) Wind direction and wind speed during the experiment at eZulu Flux Station during the study.

#### 4.4.4 Energy fluxes and energy balance closure

The  $R_n$  was the biggest energy flux during the measurement time with a daily mean of 71.8 ± 52 Wm<sup>-2</sup>. The daily averages of other energy fluxes were 46.2 ± 30.6, 19.6 ± 17.6 and 0.94 ± 7.5 (W m<sup>-2</sup>) respectively for H, LE and G. Highest energy fluxes were recorded during the growing season between DoY 51 and 114, 2016 and a similar pattern was observed towards the end of the year between DoY 280 and 318, 2016 (Fig. 4.6). Low  $R_n$  was largely observed during the winter period (DoY 137 – 191, 2016). During this period LE and G frequently

overshot the  $R_n$  (Fig. 4.6). The G was consistently lower than the three other fluxes during the measurement period.



Figure 4.6. a) Daily variation in sensible heat (H), net radiation  $(R_n)$ , latent heat (LE) and ground heat flux (G).

In terms of energy fluxes partitioning, most of  $R_n$  was consumed by H (62%) while 10% was accounted for by the closure term or energy balance residual (C) during the observation period (Fig.4.7). On an annual basis the evaporative fraction (EF) was 26%  $R_n$  while during the non-gowing season (DoY 123 – 213), it was 46% of  $R_n$  (rainfall = 40.6) mm and in the growing season it was 23% (rainfall = 271.8 mm).



Figure 4.7. Energy fluxes partitioning at eZulu Game Reserve during the experiment.

The daily pattern of energy fluxes was examined on typical days in February (DoY 51), March (DoY 69) and November (DoY 307). DoY 51 (LE higher than G but less than H), DoY 69 (LE higher than H and G) and DoY 307 when LE was the lowest flux during day time were selected for further investigation. In general, the energy fluxes followed a similar pattern regardless of



the month or flux partitioning. The fluxes increased during the morning and peaked at around 12h30 local time (Fig. 4.8a-c).

Figure 4.8(a-c). Daily patterns of energy balance components on three typical days in February, March and November, 2016.

The relationship between available energy and the sum of H and LE was significant (p < 0.001,  $R^2 = 0.84$ ), and the slope and intercept were 0.7 and 13.4 W m<sup>-2</sup> respectively (Fig. 4.9). The energy balance closure ratio (EBR) was 0.90 (Fig. 4.9).



Figure 4.9. Energy balance closure at eZulu Game Reserve Flux tower with 95% confidence limits.

## 4.4.5 Variation in ET at the eZulu station

The total ET (303.8 mm) recorded was 2.8% less than precipitation (P, 312.4 mm) received during the experimental period. Mean daily ET was  $0.76 \pm 0.65$  while mean daily reference evapotranspiration (ET0) was  $3.24 \pm 1.48$  mm and actual ET (AET) accounted for 23% of ET0 during the measurement period. The ET0 was higher than AET for most of the measurement time (Fig. 4.10) and the evaporative index  $\left(\frac{ET}{P}\right)$  ratio which is a measure of rain-use efficiency was 0.97 over the measurement period. On the other hand, the  $\frac{P}{ET0}$  ratio which is a measure of water supply deficit was 0.21 over the measurement period indicating that the environment was water limited.



Figure 4.10. Daily variation in reference evapotranspiration (ET0) and actual ET at eZulu during 2015 – 2016.

The daily pattern of ET showed that water loss occurs mainly during the day light hours (Fig 4.11a-c). Typical days were chosen to show the pattern of ET throughout the day during nongrowing and growing seasons. During the wet period daily ET peaked between 12h00 hours and 14h00 hours (Fig 4.11a) coinciding with periods of highest VPD of 2556.9 Pa (DoY 70, 2016). However, during the drier period, peak ET occurred in the morning before VPD reached its maximum (Fig 11b-d). For example, on 11 May (DoY 131, 2016), peak ET was reached around 11h30 yet maximum VPD was recorded at 15h00 hours. A similar pattern was observed on December 7 and 20 (DoY 341 and 354, 2015) with ET peaking between 08h30 and 09h30 yet VPD peaked later in the day. For example, on 20 December maximum ET of the day occurred at 08h30, yet VPD was low at this time at 1193 Pa, peaking at 1723.8 Pa at 11h30 hours (Fig. 11b-d). On such days, positive fluxes would stop as early as around 09h30 hours despite high and favourable atmospheric demand for ET to take place.



Figure 4.11. Pattern of ET and VPD on four different days at eZulu during: a) wet and b-d) dry period.

## 4.4.6 Relationship between ET and environmental factors

The trends of ET generally followed changes in rainfall and soil moisture. However, minimum ET was observed on DoY 306, 2016) while minimum SWC of 0.063 was observed on DoY 7, 2016. Maximum SWC (0.17) occurred on DoY 68, 2016 with a corresponding ET of 2.2 mm. Maximum ET of 2.86 mm occurred on DoY 23, 2016 when the corresponding SWC was 0.11  $m^3 m^{-3}$  (Fig 4.12a). High average daily ET values of up to 1.2 mm were also recorded when

SWC was relatively lower  $(0.063 - 0.07 \text{ m}^3 \text{ m}^{-3})$  during DoY 336 - 351, 2015 (Fig 4.12a). Mean LAI was  $0.39 \pm 0.14$  and ranged from 0.1 to 0.8 with a CV of 37%. Average SWC was  $0.09 \pm 0.016$  and the CV was 18%. The ET trend followed that of MODIS LAI (Myneni et al., 2002). Figure 4.12b shows the accumulated ET over 8-day periods to match the MOD15A LAI product availability.



Figure 4.12. Trends in ET and environmental controls: a) daily volumetric soil water content (SWC) and ET b) 8-day accumulated ET and 8-day leaf area index (LAI) at eZulu Game Reserve Station (DoY 283, 2015 - DoY 318, 2016).

The linear fit best described the relationship between abiotic and biotic factors controlling ET. The 8-day periods were chosen to investigate the relationships of ET with abiotic and biotic factors so that the analysis coincided with each new MODIS LAI value. The 8-day average SWC and 8-day average MOD LAI accounted for 64 and 39% (p < 0.001, N = 51, 8 day periods) of variation in 8-day sum of ET over the measurement period respectively (Fig. 4.13a-b). The LAI of 0.3 was able to sustain average daily ET that varied extensively (Fig. 13b). There was poor relationship between average 8-day VPD, energy fluxes and summed 8-day ET (Fig. 4.13c-e, p > 0.05, N = 32, 8-day periods).



Figure 4.13. Relationship between evapotranspiration (ET) and the main environmental controls of ET at the eZulu site: a) 8-day average volumetric soil water content (SWC), b) 8-day leaf area index (LAI) with 95 % confidence limits, c) 8-day average vapour pressure deficit (VPD), d) 8-day average net radiation ( $R_n$ ) and e) available energy ( $R_n - G$ ).

## 4.4.7 Biophysical controls of energy partitioning

To gain a better understanding of the integrated impacts of biophysical factors on flux partitioning, 8-day averages of bulk parameters and LAI were investigated. The 8-days were

chosen so that the analysis coincided with each new MODIS LAI value. Average daily decoupling factor ( $\Omega$ ) was 0.04 and there were no pronounced differences between winter (0.03) and summer (0.04) periods. Minimum average 8-day  $\Omega$  was observed in DoY 265, 2016 and this coincided with the lowest ¥ (Fig 4.14a and d) while both LAI (0.4) and  $G_s$  (0.29) were also relatively low. Generally, the trends in the ¥ and  $\Omega$  were similar, although there was much variability with respect to the former (Fig. 4.14a and c). The maximum LAI was observed by DoY 65 and it progressively declined up to 0.1 (DoY 153). It then stabilized between 0.2 and 0.4 up to DoY 318 (Fig. 14e). On the other hand 8-day average  $G_s$  was 1.37 mm s<sup>-1</sup> and high values (> 2 mm s<sup>-1</sup>) were observed between DoY 57 – 65, 201 – 217 as well as 305 – 318. Average  $G_a$  was 50 mm s<sup>-1</sup> but ranged from 12 to 126 mm s<sup>-1</sup> and it followed a similar pattern to  $G_s$  (Fig 4.14c). The average ¥ was 0.57 with differences in winter (0.73) and summer (0.49) while values >1 were observed in the non-growing season and early spring (DoY 161,177, 201, 225 and 233) and this coincided with periods of rainfall events in a context of reduced solar radiation.



Figure 4.14. Dynamics in 8-day average (DoY 51 – 318, 2016) bulk parameters and leaf area index (LAI): a) decoupling coefficient ( $\Omega$ ), b) Surface conductance ( $G_s$ ), c) aerodynamic conductance ( $G_a$ ), c) Priestley-Taylor coefficient (¥) and e) the MODIS LAI.

There was a strong relationship between  $G_s$  and SWC as well as bulk parameters ( $\Psi$ ,  $\Omega$ , p < 0.05, Table 4.3 and Fig 4.15a and b). Both the  $\Psi$  and  $\Omega$  were sensitive to  $G_s$  when the latter was < 10 mm s<sup>-1</sup> (Fig. 4.15a and b). At the same time, there was a strong positive relationship between the  $\Omega$ ,  $\Psi$  and SWC while a weak positive correlation was observed between SWC and the  $\Psi$  (Table 4.3). On the other hand, LAI was strongly correlated with SWC (p < 0.05) and negatively correlated with the  $\Psi$  (p > 0.05). In addition, LAI also marginally increased with  $G_s$  and the  $\Omega$  (p > 0.05, Table 4.3). Strong correlation between the  $\Omega$  and  $\Psi$  (p < 0.05) was also observed during the period of measurement (Table 4.3). At the same time,  $\Psi$  decreased with increasing VPD (p < 0.001 and Fig. 4.15c). Mean daily  $G_s$  was negatively correlated with VPD (Fig. 4.15d).

Table 4.3. The daily relationship between bulk parameters ( $G_s$ ,  $\Psi$ ,  $\Omega$ ) and environmental characteristics (SWC, LAI, VPD).

Relationship	Linear correlation (r)	p-value
SWC - $G_s$	0.44	0.01
LAI - $G_s$	0.08	0.08
$\Omega$ - SWC	0.63	< 0.001
SWC - ¥	0.26	0.16
LAI - Ω	0.26	0.14
LAI - ¥	-0.17	0.33
LAI - SWC	0.7	< 0.001
¥-Ω	0.64	< 0.001



Figure 4.15. Effects of surface conductance  $(G_s)$  on: a) the Priestley- Taylor coefficient (¥), b) the decoupling factor ( $\Omega$ ). Effects of vapour pressure deficit (VPD) on: c) the Priestley- Taylor coefficient (¥), d) surface conductance  $(G_s)$  and e) the decoupling factor ( $\Omega$ ).

# 4.5 Discussion

#### 4.5.1 Linking ET to environmental controls

The study sought to understand the pattern of water vapour and energy fluxes over the AT vegetation of South Africa. The results showed that the average meteorological conditions were conducive for ET to take place. The SWC was relatively stable compared to rainfall. Although rainfall and soil moisture are closely coupled, the stability in soil moisture could be linked to the intricate links between the soil-plant systems related to capillary action. This is crucial since it avails water to drive ET during the dry spells. However, it has also been established that the storage and movement of water in the soil profile is not well-known and is the least understood aspect of the hydrological cycle owing to uncertainties associated with the extent to which groundwater situated in aquifers or water derived from unsaturated flow in soils contribute to base flows and even stormflows (Jewitt, 2006).

## 4.5.2 Data quality and uncertainty in gap filling

Good quality data is essential in computing annual water and energy fluxes. In addition to post processing corrections, data were subjected to further quality scrutiny which included flux footprint analysis, site energy balance and co-spectral analysis. The eddy covariance theory is based on a number of assumptions which are rarely met in the real world (Burba, 2013). Consequently, a number of errors are bound to occur in the application of the EC theory. For example, measurement errors due to factors such as instrument or system failure are inherent in turbulent flux measurements. Therefore, it becomes prudent to screen data to achieve the highest quality and reduce uncertainties in computed fluxes. With respect to the present study, 77% of the flux data passed quality flags as described by Mauder & Foken (2004). The data availability was within the observed ranges from elsewhere. For example, Falge et al. (2001) reported data coverage of about 65% while Liu et al. (2013) recorded values of between 57 and 84%. Therefore, this high percentage of data availability contributed greatly to reducing uncertainties in the computed fluxes. The adoption of a well-established gap filling method for missing and rejected data also helped to reduce the uncertainties of calculated fluxes.

The study also checked if all low frequency parts are included in the flux measured by the EC using the ogive test. The data passed the ogive test within the 30-minute averaging window and subsequently, fluxes were calculated using this averaging window. This means that the whole turbulent range was captured within the 30 minutes averaging time and the contribution to the total flux by longer wavelengths was insignificant in this window. Hence, the fluxes

calculated within the 30-minute window are a true representation of turbulent exchanges. An analysis of energy balance closure is also a crucial yardstick to assess the accuracy of calculated fluxes. The surface energy balance is closed when the energy flux into a system is equal to the energy flux leaving the system, plus any energy storage change in the system. Using the shortened energy balance equation, results show that the available energy over-predicted the sum of H and LE. It is widely accepted that energy balance cannot be closed by experimental data (Wilson et al., 2002; Foken, 2008; Kidson et al., 2010) since measurement errors and errors in the EC method cannot adequately explain energy imbalance at the surface (Foken, 2008; Foken et al., 2012; Kim et al., 2012). Lack of energy balance closure is attributed to variations in the landscape architecture which influences the turbulent exchange and may cause advection of energy from one area to the other and the problem has been found in flux towers elsewhere (Wilson et al., 2002; Foken et al., 2012). The EC system at eZulu Game Reserve also recorded some spikes in LE that were greater than  $R_n$  and this suggests that advection occurred during some of the days. The present study found an energy balance closure ratio of 0.90 and  $R^2$  of 0.84. This result is consistent with the 70 – 90% closure observed across the globe (Wilson et al., 2002; Barr et al., 2006; Foken, 2008; Kidson et al., 2010; Kim et al., 2014). In South Africa over the savanna biome, Majozi et al. (2016) reported an average closure ratio of 0.93 (ranging from 0.44 to 3.76).

The source area was variable over time and this was linked to the overall stability of the atmosphere. During the relatively unstable months of November, January and February the mean source area was relatively smaller compared to more stable months of October, December, March, April and May as the stability parameters for respective months revealed. The values of the stability parameter may range from negative to positive infinity and the extreme values correspond to the limits of the heat flux approaching zero from the positive (unstable) and negative (stable) side, respectively. When the stability parameter is > 0, stable conditions prevail, while unstable conditions prevail when the stability parameter is < 0 (Schmid, 1994). Therefore, the size of the source area was strongly coupled with the atmospheric turbulence phenomena as determined by the stability parameter. The prevailing wind (south easterly and south westerly) ensured that most fluxes recorded were reflective of turbulent fluxes of the target vegetation. The maximum fetch of the station overshot the theoretical limit during absolute stable times. This shows that the theoretical 1:100 m for a fetch reported in literature (Foken et al., 2012) can be violated.

## 4.5.3 Attribution of water flux

Surprisingly, high ET rates were recorded during a dry spell and when SWC was low (Fig. 4.2e and 4.12a and b). This suggests that the recorded SWC may not be reflective of the amount of water available for ET since the water content reflectometers were buried just 60 mm in the soil, yet more moisture could be available to the deeper roots. Therefore, locating such sensors at different depths could be crucial to capture dynamics in plant available moisture. It can also be explained by the nature of vegetation where the measurements were collected. It is well established that facultative CAM plants such as P. afra have high water storage capabilities within their tissues and have relatively low stomatal densities and lower conductance to water vapour (Borland et al., 2009; Carr, 2013). CAM plants are also able to effectively use the small amount of precipitation received in such dry areas. These characteristics enable such succulent vegetation to make maximum benefit of water absorbed by their root system in improving tissue water relations. This stored water is crucial in sustaining physiological and metabolic functions between infrequent precipitation events (Owen et al., 2016). In addition, CAM plants are able to isolate their roots from the soil through root xylem cavitation or embolism and shrinkage of root cortex which prevents reverse flux of water from the tissues into the soil at large soil water deficits. It is well established that CAM plants can survive loss of 80-90% of their water content as may occur in exceptional periods of several years without rainfall (Borland et al., 2009). Therefore, it might be possible that the ET observed at eZulu Game Reserve may also be linked to long-term past rainfall events and the ability of succulents to store water in their tissues. Therefore, this convergent evolution of succulent plants makes accounting for ET and for the source of water for these plants quite difficult to attribute during periods of SWC deficits.

#### 4.5.4 Water vapour and energy fluxes trends

An analysis of the diurnal pattern of ET was quite revealing in terms of biophysical controls to water loss. Generally, it is envisaged that the diurnal pattern of ET should peak around midday when VPD is highest. However, results showed a variant from the expected. During conditions of moisture deficit in the landscape, ET peaked early between 08h30 and 09h30 local time yet maximum VPD occurred later in the day. This suggests strong biological control to ET in the AT biome as the plants could be closing their stomata earlier in the day and during periods of unfavourable VPD in order to optimise water use. This was also confirmed by the relationship between VPD and bulk parameters ( $G_s$ ,  $\mathbf{X}$ ) which was negative, suggesting that stomatal conductance was also important in regulating transpiration. However, at higher VPD, ¥ became asymptotic and such a pattern has been reported elsewhere (Jia et al., 2016). This result is consistent with the feedback and feedforward explanations for stomatal response to VPD described by Schulze (1986) and Duursma et al. (2014). The results also demonstrate the ability of the AT to optimise water use under conditions of moisture deficit and is consistent with the widely held view of drought avoidance associated with facultative CAM plants (Borland et al., 2009; Owen et al., 2016). This is also consistent with the functional convergence theory (Reich, 1997; Reich et al., 2003) that plants have evolved to optimise resource use. Results also suggest that most of the ET in the AT took place during daylight regardless of environmental constraints to ET, suggesting that the AT may not be completely closing their stomata during the day but that the plants are opportunistic in their quest to exchange water vapour for carbon. This is not consistent with the generally held view that CAM plants completely close their stomata during the day (Borland et al., 2009; Herrera, 2009; Al-Busaidi et al., 2013). The evaporative index was close to unity and it was similar to the summer value (> 0.9) reported by Jia et al. (2016) in China over a shrubland. The highest daily ET observed was 2.86 mm and this was lower than the 6 mm maximum recorded by Jarmain et al. (2004) in the Valley Thicket, Noodsberg, South Africa. This system was different from the present study site with rainfall > 800 mm. The result was also similar to the 3.3 mm observed by Jia et al. (2016) in northern China but different from the 4.5 - 5 mm reported by Dzikiti et al. (2014) in the Fynbos Biome in South Africa. Annual ET of 303.4 mm was less than that reported by Palmer et al. (2014) in the semi-arid savanna at Skukuza (331 mm) and it was also less than that reported by Finca et al. (2015) in the grassland, South Africa (332 - 378)mm).

In addition, on an annual basis, average daily LE was the smallest flux compared to  $R_n$  and H throughout the measurement period and this was similar to other studies in semi-arid regions (Jia et al., 2016). Hence, most of the  $R_n$  was consumed by H and this means that ET in the area is essentially water limited since abundant energy was available to drive the turbulent transfers of energy. The evaporative fraction was higher in winter than in summer due to reduced  $R_n$  in a context where intermittent rains were experienced. Jarmain et al. (2004) also reported similar results during the non-growing period/ winter in the Valley Thicket in Noodsberg, South Africa with most  $R_n$  being consumed by LE. The average evaporative fraction was 0.26 and it was similar to the 0.27 and 0.18 – 0.29 reported by Jia et al. (2016) and Krishnan et al. (2012) respectively in semi-arid areas. However, the results were lower than the 0.39 – 0.45 observed by Hao et al. (2007) in a Mongolian steppe.

ET is a complex biophysical process modulated by abiotic and biotic factors. The main abiotic factors investigated in this study include net radiation, RH, SWC, available energy, VPD and rainfall. The results indicated that SWC was individually, the most influential abiotic factor at the study site, accounting for much of the variation in ET. This is not surprising since moisture is a prerequisite for ET to take place. Results suggest complex relationship between VPD and ET. During wet periods ET followed VPD but during dry periods the two were not in sync, suggesting biotic control due to stomata behaviour. Both available energy and  $R_n$  had poor correlation with ET. These dynamics help to show that ET in the AT is water limited. The poor correlation of ET with energy fluxes and VPD does not imply that these are not important for ET to take place but reflect that they were not limiting in this environment. With respect to biotic factors, the LAI was analysed. The ET pattern followed that of LAI which also followed the rainfall/ SWC trend. The LAI accounted for 39% variation in ET and the relationship was significant (p < 0.001). This result is consistent with that reported by Li et al. (2007) who found that LAI explained between 21 - 47% of the variation of ET in the Mongolian steppe. This study also noted that maximum ET recorded between 08h30 and 09h30 hours at the lower end of the VPD gradient is suggestive of a strong biotic control of ET related to the opening and closure of the stomata. Therefore, biotic factors influenced ET through LAI and the convergent evolution of the AT related to its water storage capacity and the ability of the dominant facultative CAM plants to control stomatal conductance. These eco-physiological characteristics are likely to promote higher water use efficiency in the study site as reported elsewhere (for example, Herrera, 2009; Owen et al., 2016). However, these results are in sharp contrast with findings by Wang et al. (2012) who noted no meaningful relationship between ET and biotic factors represented by LAI in grasslands of Inner Mongolia. The contrasting results can be explained by vegetation characteristics.

#### 4.5.6 Integrated biophysical control of energy partitioning

In order to have a better understanding of the water and energy fluxes partitioning bulk parameters related to  $\Omega$ ,  $G_s$  and  $\Psi$  were investigated. The  $\Omega$  indicates the contribution of the integrated impacts of  $G_s$ ,  $R_n$  and VPD to the ET process. The strong couplings between SWC and bulk parameters ( $G_s$  and  $\Omega$ ) suggested strong stomatal and VPD control on the ET process. This was confirmed by the low  $\Omega$  observed suggesting that ET was largely controlled by VPD and  $G_s$  and the canopy was strongly coupled with the boundary layer. These results are consistent with previous studies (Jia et al., 2016; Krishnan et al., 2012; Odongo et al., 2016).  $R_n$  was not very influential and not limiting (average = 71.8 Wm<sup>-2</sup>) as results revealed poor correlation between energy fluxes  $(R_n - G, R_n)$  and ET during the observation period. The average  $\Omega$  was 0.03 (non-growing season) and 0.04 (growing season) respectively. These results are consistent with Mamadou et al. (2016) who observed values ranging from 0.05 -0.45 during the dry and wet season respectively in northern Benin. The lower values from this study are indicative of the degree of aridity since the annual rainfall received was 312.4 mm while the Benin study area received rainfall >1000 mm. Similar results were observed by Odongo et al. (2016) who found that during the dry season ET was more strongly linked to VPD and  $G_s$  compared to  $R_n$  in the Lake Naivasha basin in Kenya. In addition, higher  $\Omega$  has been reported during periods of high SWC (Tong et al., 2016; Tian et al., 2016). The  $\Omega$  was positively correlated with ¥ and SWC and this was consistent with results by Tong et al. (2016). The  $\Omega$  was strongly correlated with  $G_s$  but poorly correlated with LAI. However, other studies found better correlations between  $G_s$  and LAI indicating the role of canopy characteristics in partitioning fluxes (Jia et al., 2016; Tong et al., 2016). Based on the Jarvis & McNaughton (1986)  $G_s$  modelling approach adopted, the results were not surprising since the LAI was relatively low (0.1 - 0.8) during the study period. LAI generally provides a surface area for ET to take place. It should be noted that  $G_s$  is a bulk parameter accounting for ET from the surface and the canopy (Monteith, 1965; Leuning et al., 2008) and it is believed to be reflective of canopy conductance in areas with high LAI (Tian et al., 2016). However, it is well established that in addition to canopy structure, stomatal conductance is crucial in determining water vapour fluxes (Farquhar & Sharkey, 1982; Schulze, 1986; Schulze et al., 1994). The present study area lies over the AT which tends to control ET through stomatal behaviour (Mills & Cowling, 2006; Borland et al., 2009; Herrera, 2009). In addition, an examination of daily ET and VPD in this study revealed strong stomatal control of the ET process (Fig. 4.11). Therefore, the poor correlation between LAI and bulk parameters was most likely a consequence of the low and generally stable LAI and this may not necessarily be indicative of insignificant contribution to ET from the canopy given that stomatal conductance plays a crucial role in such vegetation that has evolved to avoid drought. A better understanding of stomatal behaviour is important in order to improve the accounting for water and energy fluxes over vegetated surfaces. The results also revealed that  $G_a >> G_s$  and this suggests that ET was essentially driven by VPD and  $G_s$  and the system was water limited.

The low average  $\underbrace{10.57}$  suggests that the study area was moisture limited and this was consistent with results from other semi-arid environments. For example, Odongo et al. (2016) in Kenya found values < 0.6 and so did Tong et al., (2016) in China. The evaporative index

(0.97) and the low (0.23) ET/ET0 ratio as well as the dominance of H over LE confirmed that the environment was water limited. According to the hydro-meteorological framework proposed by Zhang et al. (2001), the evaporative index approached 1 or > 1 in water limited ecosystems while it was relatively lower in energy limited systems. There was a strong relationship between  $\mathbf{X}$  and  $G_s$  and this was indicative of the interactive impacts of SWC, LAI and photosynthesis capacity (Tong et al., 2016). The study found that at  $G_s > 10 \text{ mm s}^{-1}$ , ¥ becomes insensitive and this result was similar to findings from elsewhere (Odongo et al., 2016; Tong et al., 2016). Although neither LAI nor SWC were significantly correlated with the ¥, the latter had a higher correlation coefficient, suggesting that SWC had more leverage on partitioning fluxes than LAI owing to the patchiness of the canopy. At the same time, this result suggests that the integrative bulk parameter,  $G_s$  was more influential than each of its different components (canopy and soil surface) and this was consistent with findings by Jia et al. (2016). However, it would be more useful to quantify the components of  $G_s$  in order to understand the contribution by the canopy and soil surfaces. Recent efforts have successfully disaggregated canopy and surface conductance (Morillas et al., 2013; Zhang et al., 2010; Zhang et al., 2016). However, ¥ was also negatively correlated with VPD, suggesting strong influence of SWC to ET. The negative relationship between  $\mathbf{Y}$  and LAI is due to the fact that  $\mathbf{Y} \ge 1$  were recorded between DoY 161 and 233 (winter) and this coincided with the period of limited growth resulting in little biological response in the form of LAI. Hence, during winter months, ET was essentially energy limited.

#### 4.6. Conclusion

The study sought to understand ET trends in the AT of South Africa. The data was within the acceptable data availability thresholds and therefore adaptable for long-term computation of ET. Rigorous quality control helped to reduce uncertainties in the calculated fluxes. ET in the study area was essentially water limited as much of the  $R_n$  was consumed by H and also the difference between potential ET and AET was high. In terms of environmental controls to ET, SWC and plant development represented by LAI were the most influential factors in controlling ET. In the study area, the canopy was strongly coupled with the atmospheric boundary layer as revealed by low  $\Omega$  and the low  $\Psi$  suggests that the area was water limited. The results highlighted strong complex biophysical control of the ET process as the  $G_s$  which together with VPD determined ET in the study area. The relationship between VPD and ET on onehand and bulk parameters on the other suggest that the ecosystem exercised strong biotic control to

the ET process mainly through stomatal conductance. While  $G_s$  is an important parameter, it will be more useful to disaggregate the contribution of the soil surface and canopies to this parameter especially in areas of low LAI. The strong biotic control suggests the need for further environmental plantings for vegetation with high water use efficiency, such as *P. afra*, in these water limited systems to sequester more carbon.

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# CHAPTER 5: MODELLING EVAPOTRANSPIRATION USING A MODIFIED PENMAN-MONTEITH EQUATION AND MODIS DATA OVER THE ALBANY THICKET IN SOUTH AFRICA

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OG was part of a small team (OG, ARP and SKM) that installed the eddy covariance system in the Albany Thicket. OG assisted with the in-field installation, calculated system parameters for use in the EddyPro® 6.0 software, analysed all the water and energy fluxes using EddyPro® and wrote the manuscript. OG was also responsible for writing the R code used in this chapter.

# 5.1 Abstract

Evapotranspiration (ET) is one of the least understood components of the water cycle, particularly in data scarce areas. In a context of climate change, evaluating water vapour fluxes of a particular area is crucial to help understand dynamics in water balance. In data scarce areas, ET modelling becomes vital. The study modelled ET using the Penman-Monteith-Leuning (PML) equation forced by Moderate Resolution Imaging Spectroradiometer (MODIS) leaf area index (LAI) and MODIS albedo with ancillary meteorological data from an automatic weather station (AWS). The study area is located in the Albany Thicket (AT) Biome of South Africa and the dominant plant species is Portulacaria afra. The biggest challenge to the implementation of the PML is the parameterisation of surface and canopy conductance. The study tested the use of volumetric soil water content  $(f_{SWC})$ , precipitation and equilibrium evaporation ratio  $(f_{zhang})$  and the rate of soil drying after precipitation  $(f_{drying})$  approaches to account for the fraction (f) of evaporation from the soil. ET from the model was validated using an eddy covariance system (EC). Post processing of EC data was implemented using EddyPro® software. The root mean square observations standard deviation ratio (RSR) for the three approaches was 0.1 and the root mean square error (RMSE) exceeded the mean absolute error by  $\leq$  30%, indicating good simulation despite strong phenological control to ET. The unsystematic RMSE (65%) and percent bias (-0.06%) revealed that the  $f_{drying}$  was better able to simulate ET, reinforcing the importance of using different model evaluation metrics. Evaporation from the soil  $(E_s)$  dominated total ET, suggesting that there is scope to improve water productivity. The convergent evolution of the vegetation has resulted in high plant available water than the model can detect particularly during periods of little rainfall. It is vital to quantify plant available water in order to improve ET modelling in the AT.

*Keywords:* Penman-Monteith-Leuning equation, eddy covariance, evapotranspiration, Albany Thicket

# **5.2 Introduction**

Evapotranspiration (ET) represents the combined loss of water from surfaces and through vegetation stomata. It is one of the least understood processes of the hydrological cycle yet it represents the biggest flux after precipitation (McMahon et al., 2013; Liou & Kar, 2014). Therefore, accurately determining ET is vital, particularly in a context of global changes associated with climate change. It has been established that conventional water resources and methods of water supply are stretched and may not be able to meet global water demand within

the purview of these global changes (Liou & Kar, 2014). Despite this much effort to increase water availability for agriculture has been through adding blue water and ignoring the need to manage the green water component which could improve water availability for production systems (Liou & Kar, 2014). At the same time it is envisaged that in future green water use will increase given that many regions of the world have stretched their blue water resources to the limit and so improving green water management will be critical in enhancing global food production systems (Hoff et al., 2010; Liu & Yang, 2010). This recognition has further increased the impetus to try and understand the ET process on the earth. ET or its energy equivalent, latent heat flux (LE) is crucial in the planetary energy balance which in turn determines global air circulation. Global land-atmosphere modelling initiatives linked to global change studies rely on a better understanding of the exchange of energy, water vapour and carbon dioxide between land-atmosphere systems (Barbour et al., 2005). However, ET measurement is a daunting task since there are a number of uncertainties associated with accurately characterizing ET (Amatya et al., 2016). Consequently, a number of measurement approaches have been developed including the Bowen ratio, EC systems, scintillometers and lysimeters (Amatya et al., 2016). However, these measurement methods are essentially point samples, costly, time consuming, labour intensive and sometimes subject to instrument failure (Liou & Kar, 2014). Therefore, modelling ET remains an important exercise in order to offset some of the challenges associated with the measurement methods. Furthermore, in a context of patchy measuring stations and general meteorological data scarcity, modelling may be the key to understanding ET. Hence, parameterising models in such data scarce environments could be useful in attempts to understand ecohydrological processes.

Much of ET modelling is based on the classical works of Thornthwaite, Priestley and Taylor and Penman-Monteith (Fisher et al., 2008) and the latter approach being more theoretically robust (Moran et al., 1996; Cleugh et al., 2007; Fisher et al., 2008; Zhang et al., 2008). The classical Penman-Monteith (PM) equation (Monteith, 1965) originally evolved as a big leaf model. However, in semi-arid areas characterised by patchy and short vegetation or in areas with LAI < 2.5 (Villagarcía et al., 2007; Leuning et al., 2008), such an approach may not be adequate since  $E_s$  is also critical. Consequently, a number of workers have subsequently enhanced the skills of the PM to account for evaporation from many layers (Leuning et al., 2008; Zhang et al., 2010; Morillas et al., 2013; Zhang et al., 2016). This has resulted in the PM equation increasingly becoming a dual layer model. The partitioning of ET into transpiration and  $E_s$  has been a subject of investigation for a while. The fraction of evaporation from the soil (f) is essentially a function of volumetric soil water content (SWC) in the upper layers of the soil and it is well known that it follows three stages (Ventura et al., 2006; Morillas et al., 2013). Stage 1 is designated as an energy limited phase when enough soil water is available for evaporation to occur at a maximum rate and is similar to evaporation from a surface of free water (f = 1). This phase ends when the soil moisture content in the upper layer decreases and the soil matric potential reaches a critical value. Stage 2 is symptomatic of a falling ET rate when soil is drying and water availability and soil hydraulic properties that determine the transfer of liquid and vaporized water to the surface limits the soil evaporation rate (0 < f < 1). In stage 2, the flux of water moves in the liquid and vapour forms. On the other hand, stage 3 depicts a period when the soil is dry and  $E_s$  can be considered negligible (f = 0). In this stage  $E_s$  is essentially a function of soil physical and adsorbing characteristics (Ventura et al., 2006). Therefore, a robust ET model in semi-arid areas with LAI < 2.5 should be able to capture these dynamics in order to reproduce observed ET. A recent formulation of the PM equation called the Penman-Monteith-Leuning (PML, Leuning et al., 2008; Zhang et al., 2010; Morillas et al., 2013; Zhang et al., 2016) is promising to simulate the soil drying dynamics.

The PML model built on the preceding modelling work (Cleugh et al., 2007; Mu et al., 2007). Cleugh et al. (2007) found that the PM equation was superior to the aerodynamic resistancesurface energy balance model of calculating ET. They used a simple linear relationship between surface conductance  $(G_s)$  and the remotely sensed leaf area index (LAI) obtained from the MODIS 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 and air temperature. They also introduced a separate term for  $E_s$ . 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  $G_s$  based on the biophysical understanding of leaf and canopy level plant physiology, radiation absorption by plant canopies and evaporation from the underlying soil surface. The  $G_s$  was seen as a function of canopy conductance  $(G_c)$ , which in turn was influenced by maximum stomatal conductance  $(g_{sx})$  of leaves and energy available at the canopy as well as at the soil surface. 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. The  $g_{sx}$  and f required to parametrise  $G_s$  were estimated using optimization. The new  $G_s$  model improved ET estimates when tested against flux tower data in different environments. Despite, the progress by Leuning et al. (2008) 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 days intervals. However, in semi-arid zones characterized 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  $(f_{SWC})$ ,
- (ii) application of the  $f_{Zhang}$  method and
- (iii) Application of the  $f_{drying}$  approach.

Morillas et al. (2013) found that determining the (*f*) component as a function of soil drying after precipitation  $(f_{drying})$  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  $(f_{SWC})$ .

This work tests the performance of the PML equation over the AT Biome of South Africa. The study area presents interesting space for testing the model since it is located in a dry landscape dominated by the facultative Crassulacean Acid Metabolism (CAM) photosynthesising *P. afra*. It has been established that such vegetation type has high water storage capacity within its tissues and has a very high water use efficiency (Borland et al., 2009; Carr, 2013; Owen et al., 2016). These characteristics predispose the land-atmosphere water vapour transfer to be strongly coupled to plant phenological dynamics. In South Africa, *P. afra* has received renewed interest in global change studies since it is believed to be a net carbon sink and hence its widespread environmental plantings within the context of the clean development mechanism (Mills & Cowling, 2006). Therefore, it will be interesting to test if routine meteorological data from AWS, remotely sensed LAI and albedo could capture the dynamics of evaporation over such a complex landscape.

# 5.3 Description of the PML

The PML model advanced the application of the PM equation by translating it into a two source model (Leuning et al., 2008). The PML is expressed as:

$$\lambda E = \frac{\varepsilon A_c + (\rho C_{p/\gamma}) D_a G_a}{\varepsilon + 1 + \frac{G_a}{G_c}} + f \frac{\varepsilon A_s}{\varepsilon + 1}$$
[5.1]

where the first part represents evaporation from the canopy and the second that from the soil, the terms  $A_s$  and  $A_c$  (M J m<sup>-2</sup>) are energy absorbed by the soil and canopy respectively,  $G_c$  is canopy conductance (m s<sup>-1</sup>),  $\lambda E$  is latent heat energy (Wm<sup>-2</sup>), f is a factor which modulates potential evaporation rate at the soil surface expressed by the equilibrium soil evaporation  $(E_{eq,s})$  (Priestley & Taylor, 1972); where  $E_{eq,s} = \epsilon A_s/(\epsilon + 1)$ ,  $D_a(kPa)$  is  $e * (T_a) - e_a$  which is the water vapour pressure deficit (VPD) of the air (humidity deficit), in which  $e * (T_a)$  is the saturation water vapour pressure at air temperature and  $e_a$  is the actual water vapour pressure,  $G_c$  is canopy conductance (m s<sup>-1</sup>),  $G_a$  is the aerodynamic conductance (m s<sup>-1</sup>),  $\gamma$  is the psychrometric constant,  $\rho$  is air density (kg m<sup>-3</sup>),  $C_p$  is specific heat capacity of air (J kg K<sup>-1</sup>),  $\epsilon$  is slope (s) of the curve relating saturation water vapour pressure to temperature divided by the psychrometric constant ( $\gamma$ ) i.e.  $\frac{s}{\gamma}$  and is expressed in (kPa K<sup>-1</sup>).

#### 5.3.1. Derivation of available energy (A)

Available energy is calculated as:

$$A = R_n - G \tag{5.2}$$

where  $R_n$  is net radiation and G is soil heat flux

However, for the daily calculation of ET, G was ignored following Allen et al. (1998).

# 5.3.2 Calculation of net radiation

Solar radiation ( $R_s$ ) was used to derive net radiation ( $R_n$ ), which is the difference between the incoming net shortwave radiation ( $R_{ns}$ , MJ m<sup>-2</sup> day<sup>-1</sup>) and the outgoing net longwave radiation ( $R_n l$ , MJ m<sup>-2</sup> day<sup>-1</sup>) and was calculated as follows (Allen et al., 1998):

$$R_n = R_{ns} - R_n l \tag{5.3}$$

The net shortwave radiation ( $R_{ns}$  MJ m<sup>-2</sup> day<sup>-1</sup>), resulting from the balance between incoming and reflected solar radiation, is given by:

$$R_{ns} = (1 - \alpha)R_s,$$

where  $\alpha$  is surface albedo.

Outgoing net long wave radiation was calculated following Allen et al. (1998):

$$R_n l = \sigma \left[ \frac{T_{max,K^4} + T_{min,K^4}}{2} \right] (0.34 - 0.14\sqrt{e_a}) \left( 1.35 \frac{R_s}{R_{so}} - 0.35 \right)$$
[5.4]

where  $R_n l$  is net outgoing longwave radiation (MJ m<sup>-2</sup> day<sup>-1</sup>),  $\sigma$  is Stefan-Boltzmann constant (4.903 \* 10<sup>-9</sup> MJ K<sup>-4</sup> m<sup>-2</sup> day<sup>-1</sup>),  $T_{max,K^4}$  is maximum absolute temperature during the 24-hour period (K = °C + 273.16),  $T_{min,K^4}$  is minimum absolute temperature during the 24-hour period (K = °C + 273.16),  $e_a$  is actual vapour pressure (kPa),  $\frac{R_s}{R_{so}}$  is relative shortwave radiation (limited to  $\leq 1.0$ ),  $R_{so}$  is clear-sky solar radiation (MJ m<sup>-2</sup> day<sup>-1</sup>), calculated as:  $R_{so} = (0.75 + 2 \, 10^{-5} \, z)R_a$  [5.5]

where z is station elevation above mean sea level (m),  $R_a$  is extra-terrestrial radiation (MJ m<sup>-</sup>  $^2$  day<sup>-1</sup>), calculated as:

$$R_a = \frac{20(60)}{\pi} G_{sc} d_r [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)]$$
[5.6]

where  $G_{sc}$  is solar constant (0.0820 MJ m<sup>-2</sup> min<sup>-1</sup>),  $d_r$  is inverse relative distance Earth-Sun, calculated as:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365}\right) J$$
[5.7]

 $\delta$  is solar declination (radians), calculated as:  $\delta = 0.409 \sin\left(\frac{2\pi}{365}\right) J - 1.39$ , where *J* is Julian day of the year,  $\varphi$  is latitude (radians), calculated as  $\varphi = \frac{\pi}{180}$  (decimal degrees),  $\omega_s$  is sunset hour angle (rad), calculated as  $\omega_s = \arccos[-\tan(\varphi)\tan(\delta)]$ .

Finally  $A_s$  and  $A_c$  were calculated as:

$$A_s = A\tau$$
[5.8]

$$A_c = A(1-\tau) \tag{5.9}$$

where  $\tau = \exp(-K_A LAI)$  and  $K_A$  is the extinction coefficient for total A, ( $K_A = 0.6$ ) and this value was obtained after sensitivity analysis by Leuning et al. (2008) and LAI is the leaf area index. The Beer-Lambert law was applied to help characterise  $A_s$  and  $A_c$ . Morillas et al. (2013) showed that the Beer-Lambert law was still accurate in open and short canopies despite reservations (Kustas & Norman, 1999). Hence, in the spirit of simplicity and accuracy and the similarity of the present study area to that of Morillas et al., (2013), the Beer-Lambert law was used to partition canopy and soil available energy.

#### 5.3.3 Canopy conductance $(G_c)$

Canopy conductance was calculated following Leuning et al. (2008):

$$G_{c} = \frac{g_{sx}}{k_{Q}} ln \left[ \frac{Q_{h} + Q_{50}}{Q_{h} \exp(-k_{QLAI}) + Q_{50}} \right] \left[ \frac{1}{1 + D_{a}/D_{50}} \right]$$
[5.10]

where  $K_Q$  is the extinction coefficient of visible radiation (0.6),  $Q_h$  is the visible radiation reaching the canopy surface that can be approximated as  $Q_h = 0.8A$  (Wm<sup>-2</sup>).  $D_{50}$  (kPa) and  $Q_{50}$  (W m<sup>-2</sup>), are the values of water vapour deficit and visible radiation flux respectively, when stomatal conductance ( $g_s$ ) is equal to half maximum stomatal conductance ( $g_s = g_{sx}/2$ ). This study used  $Q_{50} = 30$  W m<sup>-2</sup> and  $D_{50} = 0.7$  kPa and these values were derived from the calibration and sensitivity analyses conducted by Leuning et al. (2008) across 15 flux towers between 54° N and 35° S. Morillas et al. (2013) also used the same values and got encouraging results.

### 5.3.4 Aerodynamic conductance $(G_a)$

Aerodynamic conductance was calculated as:

$$G_a = \frac{k^2 u}{\ln\left(\frac{z-d}{z_{ow}}\right) * \ln\left((z-d)/z_{ov}\right)}$$
[5.11]

where z is the height of wind speed and humidity measurements; d is zero plane of displacement height,  $z_{om}$  and  $z_{ov}$  are the roughness lengths governing transfer of momentum and water vapour, k is the von Kármán constant (0.41) and u is wind speed at height z (Monteith & Unsworth, 2013). The quantities d,  $z_{om}$  and  $z_{ov}$  were estimated using d = 2h/3,  $z_{om} = 0.123h$  and  $z_{ov} = 0.1z_{om}$ , where h is canopy height (Allen et al., 1998).

#### 5.4 Material and methods

#### 5.4.1 Experimental site

The study area lies on the eZulu Game Reserve (EGR) situated 70 km west of Grahamstown, South Africa (33° 01' 08.929" S 26° 04' 47.860" E) on the AT biome. The AT has been recognised as a biodiversity hotspot characterised by succulents, deciduous and semideciduous woody shrubs and dwarf shrubs, geophytes, annuals and grasses. The understorey comprises of a relatively high diversity of dwarf succulent shrubs and forbs, mainly *Crassulaceae* and *Aizoaceae* (Hoare et al., 2006). The dominating vegetation type on the field site was *P. afra*, a plant known for its facultative Crassulacean Acid Metabolism (CAM) photosynthesis (Herrera, 2009). Consequently, there is renewed interest for the plant in South Africa as it is widely used in land rehabilitation as a pioneer species (Mills & Cowling, 2006). Modelled annual pan evaporation is 1963.9 mm while long-term mean annual rainfall is 400 mm (Schulze, 1997). Further details of the study area can be found in Chapter 4 (Gwate et al., 2016).

#### 5.4.2 Micrometeorological data

Calibration and validation data were collected using an Integrated CO<sub>2</sub>/H<sub>2</sub>O Open-Path Gas Analyser and 3D Sonic Anemometer (IRGASON, Campbell Scientific Inc., Logan, Utah, USA) as described in Chapter 4 and a recap is provided here. The gas analyser provides measurements of absolute densities of carbon dioxide and water vapour, while the sonic anemometer measures orthogonal wind components. The IRGASON was located at 2.65 m above the ground. A shielded (R.M. Young 41303-5A 6-Plate Solar Radiation Shield) temperature and relative humidity probe (HC2S3, Campbell Scientific Inc., Logan, Utah, USA) was installed so that it measures temperature at the same height as the sample volume of the IRGASON in order to measure air that had similar characteristics. Both the IRGASON and the temperature probe were connected to the EC100. Further, a fast response fine wire thermocouple (FW05: 0.0005 in /0.0127 mm, Campbell Scientific Inc., Logan, Utah, USA) was placed between the upper and lower arms of the IRGASON. Other bio-meteorological sensors installed included soil heat flux (G), volumetric soil moisture (SWC), air and soil temperature probes. The installation of the heat flux plates, the soil temperature thermocouples and SWC probes were done following instructions provided by Campbell Scientific (2002). Further details on micrometeorological instrumentation were presented in Chapter 4 (Gwate et al., 2016) and a summary is presented (Table 5.1).

Table 5.1. Summary of instruments at the eZulu EC station.

Bio-meteorological variable	Instrument					
Net radiation (W m <sup>-2</sup> )	One net radiometer (NR-lite2) (Kipp&Zonen, Netherlands)					
Air temperature (°C) and Relative	HC2S3 Temperature and relative humidity Probe					
humidity (RH, %)	(Campbell Scientific Inc., Logan, Utah, USA)					
Soil heat flux (W m <sup>-2</sup> )	4x soil heat plate (HFP01, Campbell Scientific Inc., Logan,					
	Utah, USA)					
Soil temperature (°C)	2 x averaging soil thermocouples probe (TCAV, Campbell					
	Scientific Inc., Logan, Utah, USA)					
Air temperature (°C)	Fine wire thermocouple (FW05: 0.0005 in /0.0127 mm,					
	Campbell Scientific Inc., Logan, Utah, USA)					
Volumetric water content (m <sup>3</sup> m <sup>-3</sup> )	2 x water content reflectometer (CS616, Campbell					
	Scientific Inc., Logan, Utah, USA)					
Wind speed (m s <sup>-1</sup> ) and direction	IRGASON					
(degrees)						

Bio-meteorological probes were connected to a CR3000 data logger (Campbell Scientific Inc., Logan, Utah, USA) for data recording. Data were saved onto a 2 GB compact flash memory card with the capacity to store up to six weeks of high frequency (20 Hz) data. The EC system was powered by two solar panels (SDT800 - 12V 80W Solar Module) that charge four 100 AmpHour deep cycle batteries (Deltec - SMF 1250 High Cycle).

# 5.4.3 Scientific grade automatic weather station data

In order to force the PML, meteorological variables required include solar radiation, air temperature, relative humidity (RH), wind speed and rainfall. Daily meteorological data were obtained from the scientific grade AWS *in situ* (Table 5.2). These data are completely independent from the EC system and provide an opportunity to compare ET derived from a routine weather station with that from the EC system. Details of the derivation of other meteorological variables such as vapour pressure and atmospheric pressure for forcing the PML and meteorological data gap filling procedures can be found in Appendix B.

Weather parameter	Instrument			
Solar radiation (MJ m <sup>-2</sup> )	Pyranometer (LI-200SA*)			
RH (%) and Air temperature(°C)	Vaisala HMP60 Temp/Humidity probe (HMP60)			
Wind speed (m s <sup>-1</sup> ) and direction (degrees)	R.M. Young wind sentry wind set (10FT			
	LEAD, Model 03001)			
Rainfall (mm)	Te525mm-L Texas electronics rain gage			
	0.1MM (0.00394 INCH, TE525 mm-L)			

Table 5.2. Summary of instruments at the automated weather station.

#### 5.4.4 MODIS data

#### Leaf area index (LAI)

The Moderate Resolution Imaging Spectroradiometer (MODIS) is an instrument on Terra and Aqua satellites that provide comprehensive series of global observations of the Earth's land, oceans, and atmosphere in the visible and infrared regions of the spectrum. The study used the MODIS LAI that is produced using the MOD15A2 fraction of photosynthetically active radiation/leaf area index (fPAR/LAI) algorithm (Myneni et al., 2003) to force the PML model. This is a freely available product with an 8-day temporal and 1 km spatial resolution. The study obtained MOD15A collection 5 from the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL-DAAC, http://lpdaac.usgs.gov) to get average LAI values to force the PML. The fPAR and LAI are biophysical variables that describe canopy structure and are related to functional process rates of energy and mass exchange (Myneni et al., 2003). It should be noted that in the PML model, LAI facilitates the partitioning of fluxes in the land-atmosphere continuum. The model used in the extraction of LAI can be found in Appendix C.

# Nadir Bidirectional Reflectance Distribution Function Adjusted Reflectance (NBRDF) product (MCD43B4)

Remotely sensed albedo required for the calculation of  $R_n$  was also obtained from the MODIS. The study applied the NBRDF (MCB43B4) product (Strahler & Muller, 1999) from the ORNL-DAAC website (http://lpdaac.usgs.gov) with a 1 km spatial and 8-day temporal resolution. Subsequently, the equation developed by Liang (2001) was applied using the six MODIS bands in order to derive shortwave albedo as follows:

 $\alpha_{short} = 0.160 \ \alpha_1 + 0.291 \ \alpha_2 + 0.243 \ \alpha_3 + 0.116 \ \alpha_4 + 0.112 \ \alpha_5 + 0.081 \ \alpha_7 - 0.0015$  [5.12]

where  $\propto_{short}$  is shortwave albedo and  $\propto_1$  is the spectral band (1-7)

The model used in the extraction of surface albedo extraction can be found in Appendix D.

#### 5.4.5 Micrometeorological data analysis

Micrometeorological data were downloaded from the eddy covariance system and sorted for further analysis in EddyPro® version 6.0 (https://www.licor.com/env/products/eddy\_covariance/eddypro.html) software. Details of post processing were presented in Chapter 4 (Gwate et al., 2016). In summary post processing included axis rotation for tilt correction, time lag compensation as well as implementation of statistical tests for raw data screening following Vickers & Mahrt (1997).

# 5.4.6 Determining the fraction of soil evaporation (f) and maximum stomatal conductance ( $g_{sx}$ )

Three methods for determining the fraction of soil evaporation (f) were tested in order to fully implement the PML equation. These include the  $f_{Zhang}$  (Zhang et al., 2010),  $f_{drying}$  (Morillas et al., 2013) and measured volumetric soil water content ( $f_{SWC}$ ) to parameterise surface conductance. The  $f_{Zhang}$  method is based on determining the proportion of evaporation from the soil as a function of accumulated daily precipitation and equilibrium ET ( $E_{eq,s,i}$ ) both in mm over N days expressed as:

$$f_{Zhang} = \min\left(\frac{\sum_{i=15}^{i} P_i}{\sum_{i=15}^{i} E_{eq,s,i}}, 1\right)$$
[5.13]

where  $P_i$  is the accumulated daily precipitation and  $E_{eq,s,i}$  is the daily soil equilibrium evaporation rate for day *i* over a number of days (N) and this study used N = 16 days (day *i* to 15 preceeding days) after sensitivity analysis by Morillas et al. (2013).

On the other hand the  $f_{drying}$  approach estimates daily values of f in two ways. Firstly, it adapts the  $f_{Zhang}$  method to days that received effective rainfall and secondly, if no effective precipitation was received, f is obtained as a function of soil drying after effective precipitation. The  $f_{drying}$  method is expressed as:

$$f_{drying} = \left(\min\left(\frac{\sum_{i=15}^{i} P_i}{\sum_{i=15}^{i} E_{eq,s,i}}, 1\right) \text{ when } P_i > P_{\min} \right)$$

$$= f_{LP} \exp(-\dot{\alpha}\Delta t) \text{ when } P_i < P_{\min}$$
[5.14]

where  $P_i$  is the accumulated daily precipitation,  $P_{min}$  is effective precipitation,  $f_{LP}$  is the f value for the last effective precipitation day,  $\Delta t$  is number of days between this (i.e. last

effective precipitation day) and the current day *i* and  $\dot{\alpha}$  (day<sup>-1</sup>) is a parameter controlling the rate of soil drying, higher  $\dot{\alpha}$  values reflecting higher soil drying speed.

Morillas et al. (2013) considered  $\dot{\alpha}$  as a constant and estimated it by optimisation, although they acknowledged that  $\dot{\alpha}$  is related to air temperature, wind speed, vapor pressure deficit, and soil hydraulic properties and hence, it should be treated as a variable. However, following good model performance from Morillas et al. (2013) this study also considered  $\dot{\alpha}$  as a constant. Based on the CLIMWAT database (FAO, 2013), daily effective precipitation was estimated at 1.48 mm for the present study site.

Volumetric soil water content (SWC) measured by sensors was rescaled to estimate f values following Morillas et al. (2013) in order to apply the  $f_{SWC}$  approach:

$$f \begin{cases} = 1 \text{ when } \theta_{obs} > \theta_{max} \\ = 0 \text{ when } \theta_{obs} < \theta_{min} \\ = \frac{\theta_{obs} - \theta_{min}}{\theta_{max} - \theta_{min}} \text{ when } \theta_{min} \le \theta_{obs} \le \theta_{max} \end{cases}$$
[5.15]

where  $\theta_{obs}$  is observed volumetric water content,  $\theta_{max}$  is the value of  $\theta$  after a strong rainfall event,  $\theta_{min}$  is the value of  $\theta$  during the driest period.

# 5.4.7 Calibration and validation

The three methods of determining the rate of drying were then applied in order to calibrate surface and canopy conductance specific to the study site. The values for  $\dot{\alpha}$  and maximum stomatal conductance ( $g_{sx}$ ) were obtained through optimization in the R-3.1.3 software environment by exploiting the *rgenoud* package (Mebane & Sekhon, 2011; Mebane, 2015). The calibration period spanned 118 days from day of year DoY 293, 2015 – DoY 45, 2016). The optimization sought to find the values of  $g_{sx}$  and  $\alpha'$  that minimised the difference between the predicted and observed ET over a given number of days (N):

$$F = \frac{\sum_{i=1}^{N} |E_{est,i} - E_{obs,i}|}{N}$$
[5.16]

where *F* is the function to be minimized,  $E_{est,i}$  is estimated ET and  $E_{obs,i}$  is observed ET during the same day and N is the total sample number of days. The R-script for the PML and the optimisation model can be found in Appendix E. The PML model is sensitive to aerodynamic components, however, in the preliminary analysis, with the canopy height of 1 m and the measurement of aerodynamic components at 2 m, ET was successfully simulated and hence there was no need for estimating wind speed at canopy height. Model validation took place between DoY 51 to DoY 318 (2016). Simple linear regression was used to determine the relationship between the observed and predicted ET. Willmott (1982) noted that no single model evaluation index can adequately describe model performance and as such it is prudent to use different indices simultaneously. Model performance was evaluated using the root mean square (RMSE), RMSE-observations standard deviation ratio (RSR), mean absolute error (MAE) and the percent bias (PBIAS) and these were calculated as follows:

$$RMSE = [N^{-1}\sum_{i=1}^{n} (P_i - O_i)^2]^{0.5}$$
[5.17]

$$MAE = N^{-1} \sum_{i=1}^{n} |P_i - O_i|$$
[5.18]

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n} (O_i - P_i)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n} (O_i - P_i)^2}\right]}$$
[5.19]

$$PBIAS = \frac{\sum_{i=1}^{n} (O_i - P_i) * (100)}{\sum_{i=1}^{n} (O_i)}$$
[5.20]

where  $P_i$  is predicted and  $O_i$  is observed ET and  $STDEV_{obs}$  is standard deviation of the observed ET.

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

$$MSE_s = N^{-1} \sum_{i=1}^{n} (\hat{P}_i - O_i)^2$$
[5.21]

where  $MSE_s$  is systematic MSE,  $O_i$  is observed ET and  $\hat{P}_i$  is derived from  $\hat{P}_i = a + bO_i$ , i.e the linear regression between the observed and modelled ET. The unsystematic MSE is expressed as:

$$MSE_u = N^{-1} \sum_{i=1}^n (P_i - \hat{P}_i)^2$$
[5.22]

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

The MAE was used since it is less sensitive to extreme values than RMSE and it avoids the considerable artificial exponentiation that is indicative of statistical mathematical reasoning from which RMSE comes from (Moriasi et al., 2007). The RSR is also a valuable index since it helps to give insights as to a measure of what is considered a lower RMSE since RSR closer to zero indicates low RMSE and suggests better model simulation (Moriasi et al., 2007). Further to these the coefficient of determination ( $R^2$ ) and the slope and y-intercepts were investigated. The  $R^2$  ranges between 0 and 1 and it denotes the proportion of the variance in the measured data, which is explained by the model, with higher values indicating less error variance. A slope of 1 and intercept of 0 (zero) indicate good model fit and the opposite is true. PBIAS was also considered in order to determine the tendency of predicted values to be greater or smaller than the observed ET values.

# 5.5 Results

## 5.5.1 Environmental conditions during the calibration period

Environmental conditions varied considerably during the calibration period (Table 5.3). The coefficients of variation (CV) for wind speed, SWC, soil and air temperature were lower (< 20%) compared to other environmental variables (Table 5.3). A total of 108.2 mm of rainfall was received during the calibration period. Daily maximum rainfall of 19.4 mm was recorded and rainfall was the most variable environmental characteristic as shown by the high CV (331%). SWC ranged from 0.063 to 0.126 m<sup>3</sup> m<sup>-3</sup> while the minimum average daily ET recorded during the calibration period was 0.05 and the maximum was 2.86 mm. On the other hand, daily reference evapotranspiration (ET0) ranged from 0.9 to 6.6 mm with a total of 507.4 mm. Soil temperature was consistently higher than air temperature throughout the calibration period. Air temperature ranged from 11 to 32°C while a minimum of 16.4 and a maximum of 39.7 were recorded with respect to soil temperature. Relative humidity (RH) ranged from 39.2 to 85.7% while a minimum of 372.9 and a maximum of 3334.9 (Pa) vapour pressure (VPD) were observed during the calibration period. Mean daily wind speed ranged from 0.8 to 3.65 m s<sup>-1</sup>. Minimum daily solar radiation was 5.2 while the maximum was 31.3 MJ m<sup>-2</sup>. The LAI was < 1 and ranged from 0.3 to 0.7 during the calibration period.

Environmental variable	Mean± SD	Coefficient of variation (%)
Air temperature (T <sup>o</sup> C)	$22.5 \pm 4$	18
Soil temperature (T°C)	$30 \pm 4$	15.6
Wind speed (m s <sup>-1</sup> )	$1.7 \pm 0.6$	16.5
RH (%)	$64 \pm 9.7$	15.2
SWC (m <sup>3</sup> m <sup>-3</sup> )	$0.09\pm0.02$	18.5
LAI $(m^2m^{-2})$	$0.44\pm0.12$	28
ET0 (mm)	$4.4 \pm 1.5$	33.5
ET (mm)	$0.83\pm0.76$	89.6
Rainfall (mm)	$0.93 \pm 3.1$	331
Solar radiation (MJ m <sup>-2</sup> day <sup>-1</sup> )	$23.4\pm7.2$	30.7
VPD (Pa)	$1368.8\pm603.2$	44

Table 5.3. Environmental conditions during calibration period.

# 5.5.2 Model calibration

The optimised  $g_{sx}$  using the three approaches of the PML ranged from 0.0023 – 0.0039 m s<sup>-1</sup> (Table 5.4). The  $f_{SWC}$  considered relatively lower  $g_{sx}$  compared to other approaches and the

lower and upper values for rescaling SWC in order to implement the  $f_{SWC}$  approach were 0.063 and 0.17.m<sup>3</sup> m<sup>-3</sup> respectively. The  $f_{drying}$  approach considered a relatively slow rate of drying ( $\dot{\alpha} = 0.09$ ) in this semi-arid area (Table 5.4).

Table 5.4. Optimized values of maximum stomatal conductance  $(g_{sx})$  and the rate of soil drying  $(\alpha')$ .

Model	$g_{sx}$	α
f <sub>drying</sub>	0.0039	0.09
$f_{Zhang}$	0.0026	N/A.
f <sub>swc</sub>	0.0023	N/A
Parameter ranges	0.002-0.02	0 – 1

### 5.5. 3 Model validation

The lowest RMSE of 0.27 mm day<sup>-1</sup> was obtained using the  $f_{SWC}$  approach of the PML and this shows that the modelled ET was less variable compared to other approaches (Table 5.5). However, the RSR were similar and low enough (0.09 – 0.1), indicating that respective RMSE were low for the three approaches of the PML (Table 5.5). Although, the three approaches tended to overestimate ET, the  $f_{drying}$  had the lowest PBIAS (-0.06%) indicating better model simulation (Table 5.5). In addition the  $f_{drying}$  approach had highest unsystematic RMSE while the lowest was obtained with the  $f_{SWC}$  approach. The systematic component of the RMSE was highest with respect to the  $f_{Zhang}$  and the lowest was observed when the  $f_{drying}$  approach was applied (Table 5.5). Average daily ET from the  $f_{Zhang}$  approach was similar to the observed while the  $f_{drying}$  and  $f_{SWC}$  approaches predicted slightly lower and higher compared to observed ET respectively (Table 5.5). The RMSE exceeded MAE by 22, 23 and 30% for  $f_{SWC}$ ,  $f_{drying}$  and  $f_{Zhang}$  approaches respectively. Modelled  $E_s$  was the dominant flux accounting for 80 – 86% of the total flux from the three approaches.

Model	MAE	RMSE	RSR	PBIAS	Systematic	Unsystematic	Mean
					RMSE (%)	RMSE (%)	
farying	0.27	0.35	0.11	-0.06	3.4	65%	0.69±0.64
f <sub>Zhang</sub>	0.23	0.33	0.11	-0.42	11%	61	$0.72 \pm 0.73$
f <sub>swc</sub>	0.21	0.27	0.09	-0.69	5.9	46	0.73±0.67
*Average							
n n n n n n n n n n n n n n n n n n n							0.70 + 0.40
E <sub>obs</sub>							0.72±0.63

Table 5.5. Evaluation of the PML model.

\*average daily observed ET

# 5.5.4 Trends in measured and modelled evapotranspiration (ET)

ET from the three approaches of the PML followed the pattern of the observed ET (Fig 5.1a). The fluxes were averaged over 8-day periods in light of the availability of MODIS LAI. However, the model tended to overestimate ET after periods of precipitation events (Fig 5.1ac). The  $f_{Zhang}$  approach had the highest magnitude of over prediction during such periods. During periods of little precipitation, the PML tended to underpredict ET (for example DoY 89 - 105, 137 - 193, 233 - 313). From DoY 249 to 313, the two approaches were better able to simulate observed ET. On the other hand, the  $f_{SWC}$  approach over-predicted ET at the beginning and end of the validation period (Fig. 5.1a). In addition, the approaches overestimated ET when the daily observed ET was < 0.17 mm (Fig. 5.1a). The SWC was relatively consistent despite the intermittent precipitation and LAI was more responsive to precipitation than SWC (Fig 5.1b) and average 8 day ET0 was consistently higher than ET (Fig 5.1c).



Figure 5.1. Trends in observed: a) 8-day average eddy covariance system (EC) evapotranspiration (ET) and modelled evapotranspiration at eZulu station using the  $f_{SWC}$ ,  $f_{drying}$  and  $f_{Zhang}$  approaches for accounting soil evaporation, b) average 8-day volumetric soil water content (SWC), rainfall (P), MODIS leaf area index (LAI) and c) average 8 day actual ET and reference ET (ET0).

Simple linear regression was used to compare observed and modelled ET by summing up ET in 8-day periods in line with the availability of the MODIS LAI. Using the  $f_{drying}$  approach, a slope of 0.97 and an intercept of 0.01 mm were obtained ( $R^2 = 0.54$ ). On the other hand, a slope of 0.99 was obtained using the  $f_{SWC}$  and the intercept was slightly higher at 0.3 mm ( $R^2 = 0.68$ ). The slope from the  $f_{Zhang}$  was greater than unity and the intercept was 0.14 mm ( $R^2 = 0.62$ , Fig. 5.2).



Figure 5.2. The relationship between the observed sum of 8-day Eddy covariance system evapotranspiration (EC ET) and sum of 8 day modelled ET: a)  $f_{drying}$ , b)  $f_{SWC}$  and c)  $f_{Zhang}$  approaches for estimating soil evaporation. N = 34, 8-day periods.

To gain a further insight into the tendency of the model to over predict ET, the energy balance closure was investigated during the validation period. The slope of the regression between

LE + H and  $R_n - G$  when forced through zero was only 0.8 indicating a relatively poor energy closure during this period.



Figure 5.3. Energy balance closure during the the validation period at eZulu Game reserve

# **5.6 Discussion**

#### 5.6.1 Environmental conditions

The calibration took place under varied conditions as depicted by variable ranges and CV and this was representative of environmental dynamics in the study site. Therefore, results derived from model validation are credible and the calibration time period is unlikely to have influenced the results. Results also suggest that the study site was essentially water limited as shown by relatively high ET0 relative to actual ET during both the calibration and validation periods, indicating that atmospheric demand was high. The LAI was more responsive to precipitation than SWC, indicating the important role played by shallow rooted vegetation in influencing ecosystem phenology and in turn water use. It is well established that succulent vegetation have shallow roots and are able to efficiently harvest light and irregular incident precipitation (Borland et al., 2009; Owen et al., 2016). This and the high water storage potential in plant tissues may have led to errors in the signal sensed by the SWC yet the soil could have been dry.

#### 5.6.2 Model calibration

The optimised values of  $g_{sx}$  from different approaches ranged from 0.0023 to 0.0039 and they were similar to those obtained by Leuning et al. (2008) using optimization over varied landscape between 54° N and 35°S. Results from this study were also similar to those reported by Isaac et al. (2004) who observed  $g_{sx}$  of 0.003 over one of the pastureland site they studied in Wagga Wagga, Australia. In addition, results were within the limits reported in a review by Kelliher et al. (1995) for various vegetation types and superclasses. Morillas et al. (2013) also obtained higher values  $(0.0067 - 0.011 \text{ m s}^{-1})$  than those reported in the present study. Results from the present study suggest that  $g_{sx}$  is relatively low in the AT. The results were not surprising since it is well established that CAM and facultative CAM plants tend to have low stomata densities and low conductance to water vapour (Borland et al., 2009). This gives credence to the general belief that such facultative CAM vegetation tend to exercise great control of water use (Carr, 2013; Owen et al., 2016). Therefore, the optimised  $g_{sx}$  are realistic and indicate the dynamics of vegetation behaviour in the study site. The  $f_{drying}$  approach yielded the highest  $g_{sx}$  compared to the other two approaches, indicating that the model considered relatively low f values compared to the other approaches The present study found  $\alpha'$  of 0.09 and that was similar to the < 0.1 reported by Leuning et al. (2008) for the dry savannas in Virgina, Australia and Tonzi, USA. The result was also similar to the 0.137 reported by Morillas et al. (2013) in Mediterranean drylands in Spain. The relatively low  $\alpha'$ was unexpected in the study area with a precipitation (P)- ET0 ratio  $\left(\frac{P}{ET0}\right)$  of 0.24 during the validation period. A number of factors can account for this low  $\alpha'$  including the intermittent precipitation as shown from rainfall pattern during the validation period. The shallow roots associated with succulent vegetation in the study area were probably able to efficiently harvest incident precipitation which may not be adequate to get into the lower soil layers (Borland et al., 2009; Owen et al., 2016). In addition, the storage and movement of ground water is one of the least understood part of the hydrological cycle (Jewitt, 2006). As such the excess soil moisture to drive ET may not necessarily be indicative of precipitation input but strong coupling between the upper and the lower layers of the soil related to capillary action. The relative stability of SWC throughout the validation period also suggests these complex soil water relations and can also be linked to the high water content in the plant tissues. This high water content in plant tissues could have affected the dielectric permittivity underlying the measurement of SWC, resulting in higher SWC signal recorded by the probe yet in reality the

soil could have been dry. All these factors could have contributed to the relatively low  $\alpha'$  in this dry area.

#### 5.6.3 Model evaluation

# Use of SWC to estimate $f_{SWC}$

The overestimation of ET from the  $f_{SWC}$  approach was due the high f values considered by the approach and this resulted in the lowest optimised  $g_{sx}$ . This result was consistent with Morillas et al. (2013) who also found the tendency by the  $f_{SWC}$  approach to overestimate ET in Spain. The use of SWC to derive the f values is quite a delicate issue and it requires long term observation of SWC. This study did not have such long term datasets for SWC and as such the  $\theta_{max}$  and  $\theta_{min}$  thresholds were obtained from the available 401 days of observation. However, the good agreement between the observed and simulated ET ( $R^2 = 0.68$ ) in this study suggest that the  $\theta_{max}$  and  $\theta_{min}$  thresholds used for rescaling SWC were good enough. The results were similar to those from García et al. (2013) who obtained  $R^2$  of 0.74 – 0.86 in the Sahelian open woodland savanna and Mediterranean grassland with a 6 year record of SWC data. However, using the same approach, Morillas et al. (2013) reported lower correlation between the observed and predicted ET, obtaining an R<sup>2</sup> of 0.54 and 0.24 in Balsa Blanca and Llano de Juanes respectively. However, the good result from García et al. (2013) was either due to the long term availability of SWC (6 years) or it was related to the different model used that did not partition transpiration from soil evaporation but provided total ET estimates (Morillas et al., 2013). The RMSE of 0.27 mm day<sup>-1</sup> from the present study using the  $f_{SWC}$  approach in a context of observed daily ET of 0.72 mm was lower than that reported by Morillas et al. (2013) who obtained RMSE of 0.41 mm day<sup>-1</sup> against a daily average observed ET of 0.49 mm in Balsa Blanca, Spain. The same study also found a high RMSE of 0.34 mm day<sup>-1</sup> in a context of daily mean ET of 0.56 mm in Llano de Juanes, Spain. The Morillas et al. (2013) study area was characterised by Hormatophiylla spinose, Festucascariosa, Genistapumila and Hormatophiylla spinose species. The regression between the observed and predicted ET from the present study yielded a slope of 0.99 and this was better than the 1.53 and 0.84 reported by Morillas et al. (2013).

# Adoption of the $f_{Zhang}$ approach to estimate soil ET

The over prediction from the  $f_{Zhang}$  approach can be attributed to high estimated f values following periods of heavy or intermittent precipitation resulting in high simulated ET. Morillas et al. (2013) also found similar over prediction by the approach indicating the

propensity of the model to over predict during periods of high precipitation. The present study found a RMSE of 0.33 mm day<sup>-1</sup> in a context of observed daily ET of 0.72 mm and this was similar to results reported by Zhang et al. (2010) who obtained a RMSE of 0.56 mm day<sup>-1</sup> at Virginia Park in Australia where average daily ET was 1.2 mm. On the other hand, Morillas et al. (2013) reported high RMSE of 0.34 mm against a daily mean of 0.49 mm at Balsa Blanca and 0.31 mm against a mean of 0.56 mm day<sup>-1</sup> at Llano de Juanes using the  $f_{Zhang}$ . Zhang et al. (2010) also reported higher RMSE of 1.56 and 1.13 mm day<sup>-1</sup> at Dargo High Plains (R<sup>2</sup> = 0.65) and Howard Spring (R<sup>2</sup> = 0.53) in Australia respectively. The slope of the regression line between the observed and modelled ET in the present study was greater than unity (1.06) but better than that reported by Zhang et al. (2010) at Dargo High Plains (1.58). Morillas et al. (2013) also reported regression slopes that deviated greatly from unity (0.77 and 1.51) in the Mediterranean drylands. Therefore, the  $f_{Zhang}$  approach provided a better model fit in the AT than results reported by Morillas et al. (2013) in Mediterranean drylands and it was comparable to results from Zhang et al. (2010) in Virginia Park.

# Adoption of the $f_{drying}$ approach to estimate soil ET

The  $f_{drying}$  approach tended to slightly over predict ET after rainfall events, though at a relatively lower rate compared to the  $f_{Zhang}$  and  $f_{SWC}$  approaches. However, Morillas et al. (2013) did not observe over-estimation bias by the model and this discrepancy may be due the overestimated  $E_s$  owing to high available energy at EGR. The present study found a RMSE of 0.35 against the daily average ET of 0.72 and this was similar to results from Morillas et al. (2013) who obtained a RMSE of 0.22 mm day<sup>-1</sup> where average daily ET was 0.49 mm at Balsa Blanca. Morillas et al. (2013) also obtained a RMSE of 0.24 mm day<sup>-1</sup> when the daily average was 0.56 mm at Llano de los Juanes, Spain. The coefficient of determination ( $R^2 = 0.54$ ) from the present study was also similar to the 0.47 to 0.59 reported by Morillas et al. (2013) in Mediterranean drylands. The same study also reported slopes of the regression between the observed and predicted ET of 0.98 and 0.79 and this was similar to the present study where a slope of 0.97 and the intercept of 0.01 mm were observed indicating good model fit. Hence, the results from the  $f_{drying}$  approach were comparable to results from elsewhere. Ideally, temporal dynamics in  $\alpha'$  are required to accurately reproduce the daily pattern of ET. However, the use of the optimised constant showed that reasonable results can still be achieved. Therefore, future work needs to develop models that will capture temporal dynamics in this variable instead of using a constant.

# 5.6.4 Comparison of models

The three approaches of the PML were able to capture the dynamics in ET in the AT and the results were comparable with other studies. For example, Mu et al. (2011) using data from 46 flux towers across the world reported a mean RMSE of 0.84 mm day<sup>-1</sup> against a daily mean ET of 1.34 mm. This means the RMSE obtained in this study (0.27 - 0.35 mm) in a context of a daily mean ET of 0.72 mm was better than the average obtained from Mu et al. (2011). Despite good simulation by the PML approaches, during periods of little precipitation, the approaches underestimated ET. This failure by the approaches could be linked to plant available water and stomatal behaviour. The study speculates that although SWC was low, plant available water to drive ET was high owing to the convergent evolution of the AT vegetation related to great water storage capacity in plant tissues (Borland et al., 2009). This is consistent with the observed pre rainy season greening of vegetation in Africa at a time when there is great moisture deficit (Ryan et al., 2016). This greening is not connected to measured soil moisture at the upper layers of soil and hence models based on weather variables and soil moisture are not able to capture changes in leaf phenology which is critical in ET studies. Therefore, the observed trends in modelled ET are symptomatic to limitations of the model in vegetation that has evolved to avoid drought. In addition, there is a distinct possibility that some of the plants were tapping ground water. Therefore, the observed ET may not be largely connected to SWC at the upper layers of the soil. Another source of uncertainty related to model simulation is the over estimation of MODIS LAI that has been reported in areas with LAI < 0.6 (Leuning et al., 2008; McColl et al., 2011).

Although, the three approaches of the PML managed to reproduce dynamics in ET, they tended to overestimate ET as the respective PBIAS suggested. The overestimation during the periods of ET < 0.17 mm day<sup>-1</sup> was due to over prediction of  $E_s$  during a wet and cooler period. To further investigate the tendency by all the approaches to overestimate ET, the energy balance closure during the validation period was investigated and results suggest that it was relatively poor. This result suggests that the measured latent heat flux is underestimated at the EGR site and this may explain the apparent overestimation by the model. The low MAE (0.21 – 0.27 mm) from the three approaches suggests that modelled ET did not deviate significantly from the observed daily mean and hence the methods were able to capture the dynamics in ET. This was confirmed by the RMSE of these three approaches respectively. This suggests absence of outliers or variance in the differences between the estimated and observed ET (Legates & McCabe, 1999) and that is the essence of a good model. Although the  $f_{drying}$  approach yielded the highest RMSE, the RSR for the three approaches were similar at  $\sim 0.1$ , suggesting that the RMSE from the three approaches were low enough and the model simulation performance was good (Moriasi et al., 2007; Golmohammadi et al., 2014). In addition, most of RMSE from the different approaches of estimating  $E_s$  was unsystematic and this indicates that the model structure captured well the system dynamics (Willmott, 1981). However, the  $f_{drying}$  approach had the highest unsystematic and lowest systematic components of the RMSE indicating the superiority of the model in simulating fluxes. Further, the tendency of the  $f_{drying}$  approach to over predict ET was significantly lower than the other approaches. The high correlation between the predicted and observed ET in this study was not necessarily suggestive of better model fit. For example the high  $R^2$  of 0.68 and 0.62 from the  $f_{SWC}$  and  $f_{Zhang}$  approaches coincided with higher overestimation bias of ET compared to the  $f_{drying}$  approach (R<sup>2</sup> = 0.54). These results are consistent with the views held by Willmott (1981) that correlation measures such as R<sup>2</sup> maybe be misleading in model evaluation and that they should be interpreted with caution. The results provide evidence that  $R^2$  does not necessarily indicate the robustness of the model as higher  $R^2$  were accompanied by a higher degree of model overestimation. Therefore, the combination of these results suggests that the  $f_{drying}$  approach was more robust and better able to simulate dynamics in ET than the other approaches in the study area.

Modelled  $E_s$  dominated the water vapour flux and this was consistent with the generally held view that evaporation from the soil could be ~ 80% of the total flux in areas of low LAI (Ventura et al., 2006; Leuning et al., 2008; Mu et al., 2011; Morillas et al., 2013; Kool et al., 2014). Understanding of the partition between transpiration and evaporation help inform management of water in crop farming, improve the interpretation of hydrological processes and help to manage water in the context of global environmental changes (Kool et al., 2014). Transpiration is associated with plant production while  $E_s$  does not directly contribute towards plant production and agriculturalists refer to it as 'unproductive water loss'. This suggest that  $E_s$ , can influence vegetation or crop production by reducing the amount of water available for transpiration (Hulugalle et al., 2017). Therefore, in water limited systems, agricultural crop yields can be enhanced through management practices that reduce  $E_s$ . In a context of climate change associated with water scarcity, it is also imperative to optimise water use and reduce 'unproductive' losses (Kool et al., 2014). In fact it is envisaged that management of ET will be critical in improving global food production systems in a context of population increase with a consequence of competition for available water resources against a background of growing water scarcity (Molden et al., 2010). The dominance of  $E_s$  suggests the need for enhancing current initiatives in South Africa for environmental plantings of *P. afra* in the study area in order to reduce the so-called 'unproductive' water loss. Within the broader context of ecosystem rehabilitation, *P. afra* is widely planted in the AT as a pioneer species since it requires little water to thrive and it is a net carbon sink (Mills & Cowling, 2006). Therefore, increased plantings of *P. afra* will simultaneously reduce 'unproductive' water loss and contribute to the reduction in the atmospheric CO<sub>2</sub>.

## **5.7 Conclusion**

The applicability of the PML in the AT of South Africa dominated by *P. afra*, was evaluated. The  $f_{drying}$  approach was better able to simulate ET than the  $f_{Zhang}$  and  $f_{SWC}$  approaches. The three approaches over-predicted ET largely because of strong phenological control to the ET process, and due to the poor energy balance closure at the site caused by possible underestimation of the latent heat flux. The convergent evolution of vegetation presented unique challenges to ET modelling. The phenological characteristics related to stomata control, the high water storage capacity of the vegetation, pre rainfall season greening and possibilities of vegetation accessing ground water make ET modelling a daunting task in the study area. As such. measured SWC may not have been reflective of plant water available for ET to occur. Hence, data on SWC may be critical in modelling ET. Future studies may investigate the relative contribution of these potential sources of water to the total flux observed in the Thicket. Despite these challenges good model fit, comparable to other studies, was observed, indicating that the PML was able to simulate ET in a context characterised by strong phenological control. It is important to use different model evaluation metrics in order to identify models providing the best simulation. The dominance of  $E_s$  suggests that there is scope to improve water productivity in the AT. Quantifying available plant water in landscapes associated with strong phenological control remains a challenge and improvement in this direction may improve the model fit. Future research should try to develop models that will be able to simulate dynamics in  $\alpha'$  in order to improve model fit.

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# CHAPTER 6: MEASURING AND MODELLING EVAPOTRANSPIRATION IN A SOUTH AFRICAN RANGELAND: COMPARISON OF TWO IMPROVED PENMAN-MONTEITH FORMULATIONS.

This chapter will be submitted to an appropriate journal for publication.

OG was part of a small team that installed the large aperture scintillometer at the two sites in the grassland biome. OG assisted with the in-field installation, calculated system parameters for use in the Evation software, analysed all the water fluxes using Evation and wrote the manuscript. OG was also responsible for writing the R code used in this chapter.

# 6.1 Abstract

Accurately measuring evapotranspiration (ET) is important in the context of global atmospheric changes and in order to inform global climate models. Direct ET measurement is costly to apply widely and local calibration and validation of ET models developed elsewhere improves confidence in ET derived from such models. This study seeks to compare the performance of two ET models, the Penman-Monteith-Leuning (PML) and Penman-Monteith-Palmer (PMP) equations, over mesic grasslands in two study sites in South Africa. The study used routine meteorological data from a scientific-grade automatic weather station (AWS) to apply the PML and PMP models. The PML was calibrated at one site and validated in both sites. The models were evaluated using ET derived from a large aperture scintillometer (LAS). The PML approach performed well at both sites with root mean square error (RMSE) within 20% of the mean daily observed ET ( $R^2 = 0.83 - 0.91$ ). Routine meteorological data were able to reproduce fluxes calculated using micrometeorological techniques and this increased the confidence in the use of data from sparsely distributed AWS to derive reasonable ET values. The PML was better able to simulate observed ET compared to the PMP since the former models both transpiration and soil evaporation  $(E_s)$  while the latter only models transpiration. Hence, the PMP systematically underestimated ET in a context where the leaf area index (LAI) was < 2.5. Model predictions in the grasslands could be improved by incorporating  $E_s$ component in the PMP approach while the PML could be improved by careful choice of the number of days to be used in the determination of the fraction of  $E_s(f)$ .

*Keywords:* Evapotranspiration, Penman-Monteith-Leuning, Penman-Monteith-Palmer equation, MOD16 ET, large aperture scintillometer, quality control, parameter estimation, canopy and surface conductance

# **6.2 Introduction**

Evapotranspiration (ET) or its energy equivalent, latent heat flux (LE), influences water availability and the partitioning of energy for a given landscape. ET is important to the long term development of regional climate as it links the energy and water cycles (Li et al., 2016). However, ET is a complex biophysical process which is influenced by various processes occurring at a local and global scale (Amatya et al., 2016). An understanding of energy and water vapour fluxes over a particular landscape is crucial especially in a context of validating climate change predictions. This will help inform global change models and also improve the ability to monitor climate change consequences. 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). Recent developments in the form of eddy covariance systems and scintillometers have reduced uncertainties associated with measuring ET. Consequently, many studies have been carried out to evaluate the ability of models in reproducing observed ET (Fisher et al., 2008; Leuning et al., 2008; Mu et al., 2011; Morillas et al., 2013). These studies frequently combine ground-based routine meteorological data and remotely sensed data in developing models.

In the developing world, long-term ET datasets from different vegetation physiognomic types are largely not available. In South Africa, the Grassland biome comprises about 27.9% of the total terrestrial surface of the country (Van Wilgen et al., 2012) and it is under pressure from land cover changes related to agriculture and settlement (Mucina et al., 2006). In the last decades the threat from woody invasive alien plants (IAPs) in the Grassland Biome has been recognised (Kotzé et al., 2010). Therefore, it is critical to identify accurate ET models for grasslands in a context of these changes. Micrometeorological techniques such as eddy covariance and scintillometry, are costly and this mitigates against their widespread adoption. At best these micrometeorological methods can be used to calibrate and validate models at a local scale. Suffice to note that most models were developed elsewhere and have not been locally calibrated or validated and application of such models remains a challenge due to a paucity of validation datasets. The availability of micrometeorological equipment in data scarce areas is useful for locally calibrating and validating models to enable widespread applications with higher confidence levels. However, the application of micrometeorological methods is fraught with many challenges owing to the underlying theory and inherent errors (Savage et al., 2004; Rambikur & Chávez, 2014). Hence, there is a need for requisite data filtering and correction whenever they are used to reduce uncertainties in the calculated fluxes.

A number of ET models have evolved, ranging from radiation, combination, energy balance and temperature based algorithms(Fisher et al., 2011; Liou & Kar, 2014; Mu et al., 2011; Zhang et al., 2016). The Penman-Monteith (PM) equation is one of the most theoretically sound ET models which is essentially driven by routine weather data from weather stations (Fisher et al., 2008; Leuning et al., 2008; Zhang et al., 2016). The PM equation evolved as a single layer potential ET model (Penman, 1948; Monteith, 1965), but recent efforts have enhanced it to also account for soil evaporation ( $E_s$ ). One of the recent formulations of the PM equation is the Penman-Monteith-Leuning (PML) equation (Leuning et al., 2008; Morillas et al., 2013). The biggest challenge in the implementation of the PML equation is the determination of canopy conductance and the fraction of soil evaporation (f). In this case, f accounts for evaporation from a surface such as bare ground or even a water surface while canopy conductance  $(G_c)$  influences transpiration. The  $G_c$  is reflective of the interaction of the soil-plant-atmosphere system and the ability of plants to draw water from the soil (Ziemer, 1979). It is assumed to be reflective of an integration of stomatal conductance  $(q_s)$ of each leaf. Hence, parameterisation of  $G_c$  requires knowledge of maximum stomatal conductance  $(g_{sx})$  (Leuning et al., 2008). It is well established that  $E_s$  is a function of energy and the rate of water conduction to the soil surface (Rictchie, 1972; Ziemer, 1979). Consequently, the equilibrium rate of evaporation (Priestley & Taylor 1972) has been widely used to account for  $E_s$  (Morillas et al., 2013; Zhang et al., 2016). Evaporation from bare soil arguably follows three distinct stages which include an initial period in which the soil is wet or saturated and ET occurs at or near to a potential rate. This is followed by a second stage whereby soil is drying and the evaporation rate depends on soil characteristics which may limit the movement of water into the surface; and lastly, dry soil in which the evaporation rate is negligible (f=0) (Hulugalle et al., 2017). Owing to this understanding, various algorithms have been developed to simulate soil drying so as to better determine  $E_s$  (for eample, Leuning et al., 2008; Mu et al., 2011; Morillas et al., 2013; Zhang et al., 2016). Therefore, proper determination of  $G_c$  and f is important in order for the model be able to capture the soil drying process and to fully account for  $E_s$ .

Other recent approaches of the PM equation connect reference ET (ET0) to actual ET by either using the leaf area index (LAI), vegetation indices (VIs) or crop coefficients ( $K_c$ ) (Allen et al. 1998; Nagler et al., 2013; Palmer et al. 2014). Palmer et al., (2014) successfully applied the LAI and ET0 to determine actual ET in a semi-arid savannah in South Africa.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 Penman-Monteith-Leuning (PML) (Leuning et al., 2008; Morillas et al., 2013) and a method described by Palmer et al. (2014) conveniently called Penman-Monteith-Palmer (PMP) equation. In addition to the theoretical robustness, these two models were selected since they simple to implement and data to drive the models was available. The main difference in the approaches is how potential ET (PET) is constrained to actual ET (AET). Essentially, the PMP uses LAI as a scalar while the PML uses canopy conductance and the f to constrain ET. The study measured ET using a Large Aperture
Scintillometer (LAS) and subsequently validated the PML and PMP models over grasslands at Truro and Somerton farms in the Eastern Cape, South Africa between September 2015 and April 2016. Validation of the ET models in data scarce areas is important so that wide area ET can be derived in such areas with a higher degree of confidence. This work comprises a brief introduction of the models to be evaluated, theoretical basis of scintillometry, methodology, results and discussions.

#### 6.3 Theoretical background

# 6.3.1 Penman-Monteith-Leuning (PML)

Chapter 5 provided detailed logistics of calculating ET using the PML (equation 5.1) and the model will not be described in this Chapter. Equations 5.2 to 5.11 and Appendix B-D were used to generate the requisite data for implementing the model.

#### 6.3.2 PMP model

This model uses the leaf area index (LAI) as a proxy for vegetation indices (VIs) or crop coefficients ( $K_c$ ) to scale reference ET (ET0) to actual ET (Palmer et al., 2014). 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., 2003), plants have evolved to calibrate leaf area and light harvesting ability according to the availability of resources in order to optimize carbon fixation, such that leaf area is a good indicator of vegetation physiological activity and plant water use. Hence, in vegetated surfaces, AET approaches reference ET (ET0) under ideal conditions of abundant soil moisture, stomatal conductance and soil nutrients 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 some fraction  $\leq 1$  (Allen et al., 1998). Following this theoretical frame, the PMP model was developed since it is believed that the relationship of LAI at a time (T1) to maximum LAI  $(LAI_{max})$  indicates the vegetation functional condition of a landscape relative to its optimal (Palmer & Yunusa, 2011; Weideman, 2013; Palmer et al., 2014). In a similar manner this relationship can be applied to relate AET to ET0 assuming that ET0 represents the upper limit of water use possible within the system when  $\frac{LAI}{LAI_{max}} = 1$ . Maximum LAI can be derived from long term data sets such as the MOD15 LAI product (Myneni et al., 2002) or maximum LAI recorded in an intact similar vegetation type. 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:

$$ET = \frac{LAI}{LAI_{max}} * ET_0$$
[6.1]

where  $LAI_{max}$  is the maximum LAI, ET0 is reference calculated using equation 6 in Allen et al. (1998):

$$ET0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 D_a}{\Delta + \gamma (1 + 0.34 u_2)}$$
[6.2]

where  $R_n$  is net radiation at the crop surface (MJ m<sup>-2</sup> day<sup>-1</sup>), G is soil heat flux density (MJ m<sup>-2</sup> day<sup>-1</sup>), *T* is mean daily air temperature at the reference (2 m) height (°C),  $u_2$  is wind speed at the reference (2 m) height (m s<sup>-1</sup>),  $\Delta$  is slope of vapour pressure curve (°C<sup>-1</sup>),  $D_a$  (kPa) is  $e * (T_a) - e_a$  which is the water vapour pressure deficit of the air (humidity deficit), in which  $e * (T_a)$  is the saturation water vapour pressure at air temperature and  $e_a$  is the actual water vapour pressure at air temperature and  $e_a$  is the actual water vapour pressure and  $\gamma$  is the psychrometric constant (kPa °C<sup>-1</sup>).

# 6.3.3 Large aperture scintillometer

A scintillometer is an instrument that can measure the amount of scattering of electromagnetic radiation caused by turbulence in the atmosphere through the transmission of a beam of light over a horizontal path between a transmitter and a receiver (Meijninger et al., 2002; Kohsiek et al., 2002; Pozníková et al., 2015). At the receiver, the fluctuation in light intensity is analysed. These refractive index fluctuations lead to intensity variations, which are known as scintillations (Kohsiek et al., 2002; Tunick, 2003). The scintillations are caused by the fluctuations of the refractive index (n) of air along the propagation path and its magnitude can be described by the structure parameter of the refractive index of air  $(C_n^2)$  which is the basic parameter derived from scintillometer data (Hill, 1992; Pozníková et al., 2015). The  $C_n^2$  m<sup>-2/3</sup> is a representation of atmospheric turbulent strength or the ability of the atmosphere to transport scalars, such as heat, humidity and other atmospheric gases. The value of  $C_n^2$  in the lower atmosphere has generally been observed to range from about 10<sup>-12</sup> to 10<sup>-17</sup> m<sup>-2/3</sup> (Kipp & Zonen, 2012). High values of  $C_n^2 (\geq 10^{-12} \text{ m}^{-2/3})$  indicate a highly unstable atmosphere while lower values ranging from  $10^{-16}$  to  $10^{-17}$ m<sup>-2/3</sup> are indicative of weak and insignificant atmospheric optical turbulence over shorter ( $\leq 2$  km) optical paths (Tunick, 2003). By applying the Monin-Obukhov Similarity Theory (MOST), surface flux of sensible heat (H) can be determined. Further, the latent heat (LE) flux can be derived from the surface energy balance, if ancillary meteorological data are available. For a LAS that has equal apertures, the relationship between

the measured variance of the natural logarithm of intensity fluctuations ( $\sigma_{lnI^2}$ ) and  $C_n^2$  is as follows (Kipp & Zonen 2012):

$$C_n^2 = 1.12 \,\sigma_{lnl^2} D^{7/3} \ L^{-3} \tag{6.3}$$

where D is the aperture diameter of the LAS, L the distance between the transmitter and the receiver (i.e. the path length). It should be noted that fluctuations in temperature (T) and humidity (Q) also influence  $C_n^2$ . Hence,  $C_n^2$ , can further be expanded into the structure parameters of temperature ( $C_T^2$ ), humidity ( $C_Q^2$ ), and their covariation ( $C_{TQ}^2$ ):

$$C_n^2 = \frac{A_T^2}{\bar{\tau}^2} C_T^2 + \frac{2A_T A_Q}{\bar{\tau}\bar{Q}} C_{TQ} + \frac{A_{Q^2}}{\bar{Q}^2} C_{Q^2}$$
[6.4]

where  $A_T$  and  $A_Q$  are functions of the beam wavelength and the mean values of temperature, absolute humidity, and atmospheric pressure. In the visible and near-infrared wavelength region of the electromagnetic range,  $A_T$  and  $A_Q$  are presented as:

$$A_T = -0.78 * 10^{-6} \left(\frac{p}{T}\right) + 0.126 * 10^{-6} R_v Q, \text{ where P is atmospheric pressure}$$
[6.5]  
$$A_Q = -0.126 * 10^{-6} R_v Q$$
[6.6]

where  $R_{\nu}$  is the specific gas constant for water vapour (461.5 J Kg<sup>-1</sup>). Values for  $A_T$  and  $A_Q$  in mean atmospheric conditions are estimated at -0.27\*10<sup>-3</sup> and -0.70\*10<sup>-6</sup> respectively (Kipp & Zonen, 2012). It has been observed that the contribution of humidity related scintillations is negligible compared to temperature related scintillations, and hence the near infrared LAS essentially 'sees' temperature related scintillations. Therefore, a simplified expression of the relationship can be derived, which enables the derivation of  $C_T^2$  from  $C_n^2$  as follows (Kipp & Zonen 2012):

$$C_n^2 \approx \frac{A_{T^2}}{T^2} C_T^2 \left(1 + \frac{0.03}{\beta}\right)^2 \text{ or } C_n^2 \approx \left(\frac{0.78 \times 10^{-6} P}{T^2}\right)^2 C_{TQ} \left(1 + \frac{0.03}{\beta}\right)^2$$
 [6.7]

where  $\beta$  is the Bowen ratio

When dry surface conditions prevail,  $C_T^2$  has been observed to be directly proportional to  $C_n^2$ :

$$C_n^2 \approx \frac{A_T^2}{T^2} C_T^2 \text{ or } C_n^2 \approx \left(\frac{0.78 * 10^{-6} P}{T^2}\right)^2 C_T^2$$
 [6.8]

Once the  $C_T^2$  is known, MOST can be applied to derive the sensible heat flux (H) from  $C_T^2$ . The similarity relation that links  $C_T^2$  to temperature scale (*T*\*) is expressed as (Wyngaard et al., 1971; Kipp & Zonen, 2012):

$$\frac{C_n^2 (Z_{LAS} - d)^{2/3}}{T^{*2}} = f_T \left( \frac{Z_{LAS} - d}{L_{OM}} \right) (L_{OM} < 0)$$
[6.9]

where d is the zero-displacement height and  $Z_{LAS}$  is the effective height of the scintillometer beam above the surface. T\* is a temperature scale defined as:

$$T \ast = \frac{-H}{\rho C_{\rm p} U \ast}$$
[6.10]

and  $L_{OM}$  is the Obukhov length:

$$L_{OM} = \frac{u^{*2}T}{gk_V T^*}$$
[6.11]

where  $\rho$  is the density of air (~1.2 kg m<sup>-3</sup>), C<sub>p</sub> is specific heat of air at constant pressure (~1005J kg<sup>-1</sup> K<sup>-1</sup>), *k* is the von Kármán constant (~0.41), *g* is the gravitational acceleration (~9.81 m s<sup>-2</sup>) and *u* \* is the friction velocity.

The universal stability function  $(f_T)$  is defined as follows for unstable conditions:

$$f_T\left(\frac{Z_{LAS}-d}{L_{OM}}\right) = 4.9\left(1 - 6.1\frac{Z_{LAS}-d}{L_{OM}}\right)^{-2/3} (L_{OM} < 0),$$
[6.12]

and for stable conditions as:

$$f_T\left(\frac{Z_{LAS}-d}{L_{OM}}\right) = 4.9\left(1+2.2\frac{Z_{LAS}-d}{L_{OM}}\right)^{\frac{2}{3}}(L_{OM}>0)$$
[6.13]

In order to derive H, the friction velocity  $(u^*)$  and surface roughness  $(z_{om})$  are also required (De Bruin et al., 1995):

$$u *= \frac{ku}{ln\left(\frac{z-d}{z_{OM}}\right) - \Psi_m\left(\frac{z-d}{L_{OM}}\right) + \Psi_m\left(\frac{z_{OM}}{L_{OM}}\right)}$$
[6.14]

where z is the height at which the wind speed is measured,  $z_{om}$  is momentum roughness length and  $\Psi_m$  is the integrated stability function for momentum for unstable day-time conditions which in this study was expressed as:

$$\Psi_m\left(\frac{z}{L}\right) = 2ln\left(\frac{1+x^2}{2}\right) = ln\left(\frac{1+x^2}{2}\right) - 2\arctan(x) + \frac{\pi}{2} \qquad (L_{OM} < 0) \qquad [6.15]$$
  
where  $x = \left(1 - 16\frac{z}{L_{OM}}\right)^{\frac{1}{4}}$ ,

and for stable conditions:

$$\Psi_m\left(\frac{z}{L}\right) = -5\left(\frac{z}{L}\right) \qquad (L_{OM} > 0)$$
[6.16]

Based on the similarity relations, the  $T^*$ ,  $u^*$ , and the  $L_{OM}$  can be solved iteratively. Subsequently, the sensible heat flux (H) was calculated as

$$H = -\rho C_{\rm p} \, u * T * \tag{6.17}$$

and

Momentum flux ( $\tau$ , kg m<sup>-1</sup> s<sup>-2</sup>) can be derived as:

$$\tau = \rho u *^2 \tag{6.18}$$

Finally, the latent heat flux (*LE*) was derived by applying the surface energy balance equation (Pozníková et al., 2015):

 $R_n = H + LE + G$ , where H and G are sensible and soil heat flux [6.19] This shortened energy balance equation assumes no advection and that energy stored by biomass and that used during photosynthesis are negligible. In addition, it is well established that over longer periods (daily), the storage terms are insignificant and balance out (Savage et al., 2004; Evans et al., 2012).

#### 6.4 Material and methods

#### 6.4.1 Study site

Two experimental sites were selected at Truro and Somerton farms in the north Eastern Cape (Fig. 6.1) and micrometeorological measurements were collected using a large aperture scintillometer (LAS). The study sites lie on the Grassland Biome (Mucina et al., 2006). The area is characterised by wet summers and dry winters. The geology of the area comprises of sandstones, silt stones and mudstones of the Karoo Supergroup (Elliot formation) with some mafic intrusions (Mucina et al., 2006). Livestock (sheep and cattle) and crop production are the main economic activities in both farms. A field campaign approach was adopted owing to logistical problems. The periods of the field campaign are provided (Table 6.1). Both sites were exposed to moderate grazing by livestock and the Truro site represents a post disturbance while the Somerton site represent an undisturbed grassland.



Figure 6.1. Location of study sites at Truro and Somerton farms.

Lat/ Lon	Lat/ Lon	ET data period	Vegetation	Elevation (m)
(Transmitter)	(Receiver)		type	
31° 9'2.00"S,	31° 9'2.00"S	DoY 309, 2015-	Grassland	1250 - 1264
28°22'50.00"E	28°23'3.00"E	DoY 104, 2016		
31° 4'10.03"S,	31° 3'59.08"S	DoY 265-DoY	Grassland	1458 - 1473
28°17'29.72"E	28°17'28.92"E	308, 2015		
	Lat/ Lon (Transmitter) 31° 9'2.00"S, 28°22'50.00"E 31° 4'10.03"S, 28°17'29.72"E	Lat/LonLat/Lon(Transmitter)(Receiver)31° 9'2.00"S,31° 9'2.00"S28°22'50.00"E28°23'3.00"E31° 4'10.03"S,31° 3'59.08"S28°17'29.72"E28°17'28.92"E	Lat/LonLat/LonET data period(Transmitter)(Receiver)31° 9'2.00"S,31° 9'2.00"SDoY 309, 2015-28°22'50.00"E28°23'3.00"EDoY 104, 201631° 4'10.03"S,31° 3'59.08"SDoY 265-DoY28°17'29.72"E28°17'28.92"E308, 2015	Lat/       Lon       ET data period       Vegetation         (Transmitter)       (Receiver)       type         31° 9'2.00"S,       31° 9'2.00"S       DoY 309, 2015-       Grassland         28°22'50.00"E       28°23'3.00"E       DoY 104, 2016       Jord 10.03"S,         31° 4'10.03"S,       31° 3'59.08"S       DoY 265-DoY       Grassland         28°17'29.72"E       28°17'28.92"E       308, 2015       Grassland

Table 6.1. Characteristics of the study area (DoY = day of year).

### 6.4.2 Truro site

The first experimental site was at Truro farm and the site was cleared of *Acacia mearnsii* and in 2005 and left to re-vegetate naturally, with some large tree stumps left *in situ*. At this site, modelled annual pan evaporation and rainfall are 1632 and 786 mm respectively (Schulze, 1997). The dominant IAP had been *A. mearnsii* prior to clearing. There was no visual evidence of re-sprouting, but germinating *A. mearnsii* seedlings were being heavily browsed by cattle, keeping them under control. Post-clearing, the dominant grass species were *Eragrostis curvula* and *Sporobolus africanus*, as well as some pockets of *Heteropogon contortus*. Mean canopy height was estimated at 0.15 m after ten physical measurements at different patches around the path length. Based on the line transect method (Flombaum & Sala, 2007), grass, bare soil, forbs and shrub canopy cover were estimated at 65, 24, 5 and 6% respectively. The average terrain slope along the path length was 7.4% with a maximum slope of 18.8%. The altitude along the LAS path length ranged from 1458 – 1473 m amsl.

## 6.4.3 Somerton site

At the Somerton site, pan evaporation is 1686 mm per year and long term mean annual rainfall is approximately 756 mm. (Schulze, 1997). The LAS system was installed in a grazing camp and the dominant grass species was *Themeda triandra*. There was no evidence of any other form of historical disturbance (e.g. ploughing) in this camp, and it represented un-disturbed native grassland in good a relatively condition. At Somerton, the line transect method (Flombaum & Sala, 2007) estimated grass, bare soil, forbs canopy cover at 90, 8 and 2% respectively. Average canopy height was 0.25 m and altitude ranged from 1250 – 1264 m amsl with an average of 0.4% slope along the LAS path.

#### 6.4.4 Large Aperture Scintillometer set up

A large aperture scintillometer (LAS MkII, Kipp & Zonen B.V., Netherlands) was installed firstly at Truro and then at Somerton during the growing season of 2015/2016. The LAS MkII Large Aperture Scintillometer is designed for measuring the path-averaged structure parameter of the  $C_n^2$  over horizontal path lengths from 250 m to 4.5 km and has a 0.149 m diameter (*D*) beam. The light source of the LAS MkII transmitter operates at a near-infrared wavelength of 850 nm. The scintillations measured by the instrument at this wavelength are caused by turbulent temperature fluctuations (Kipp & Zonen, 2012). At Truro farm a suitable patch of relatively homogenous rehabilitated grassland was found with a path length of 458 m, while at Somerton farm the path length was 355 m. Since the path lengths were less than 1 km, 0.1 m aperture diameter restrictors were fitted (Kipp & Zonen, 2012). The instrumental set up was carefully arranged to ensure that the fetch comprised relatively homogenous grassland vegetation at both study sites.

#### 6.4.5 Micro-meteorological station

A micro-meteorological station was established at the LAS receiver to measure meteorological variables. The station measured  $R_n$ , wind speed and direction, G, volumetric soil water content (SWC), air and soil temperature as well as relative humidity (RH). Micro-meteorological variables and instruments used are presented (Table 6.2). Two net radiometers (NRLite, Kipp & Zonen, Delft, The Netherlands) were used to measure  $R_n$  at 2 m above the canopy at both sites. The G was measured using four soil heat flux plates (HFP01, Campbell Scientific Inc., Logan, Utah, USA). The plates were placed at a depth of 80 mm below the soil surface. A system of parallel soil thermocouple probes (TCAV, Campbell Scientific Inc., Logan, Utah, USA) were installed at depths of 20 and 60 mm to measure soil temperature above the heat flux plates. A soil thermocouple probe measures temperature at four locations, or junctions, each consisting of type E thermocouple wire (chromel-constantan) that is enclosed within a stainless steel tube (Campbell Scientific, 2002). It works in conjunction with the soil heat flux plate to calculate the heat flux at the surface of the soil. Volumetric soil water content (CS616, Campbell Scientific Inc., Logan, Utah, USA) was measured in the upper 60 mm of soil using two sensors. The installation of heat flux plates, soil temperature thermocouples and the water content reflectometer was done following Campbell Scientific (2002). An HC2S3 temperature and RH probe (Campbell Scientific Inc., Logan, Utah, USA) was used to measure air temperature and RH. The probe is appropriate for long-term, unattended applications. Air temperature was also measured using two unshielded type-E (chromel/constantan) fine-wire thermocouples (FW05) placed at heights of 1 m and 2.7 m above the ground surface. The FW05 is a fast response Type E thermocouple with a 0.0005 in. diameter. It measures atmospheric temperature gradients or fluctuations with research-grade accuracy. Wind speed and direction were measured using an anemometer (Wind Monitor-AQ, model 05305, R.M. Young Company, Michigan, USA) locate at 2.5 m above the surface.

Bio-meteorological variable	Instrument		
Net radiation (W m <sup>-2</sup> )	Two net radiometers (NR-lite2) (Delft, Kipp		
	& Zonen, Netherlands)		
Temperature (°C) and Relative	HC2S3 Temperature and relative humidity		
Humidity (%)	Probe (Campbell Scientific Inc., Logan,		
	Utah, USA)		
Soil heat flux (Wm <sup>-2</sup> )	4 x soil heat plate (HFP01, Campbell		
	Scientific Inc., Logan, Utah, USA )		
Soil temperature (°C)	2 x averaging soil thermocouples probe		
	(TCAV, Campbell Scientific Inc., Logan,		
	Utah, USA)		
Air temperature (°C)	Fine wire thermocouples (FW05: 0.0005 in		
	/0.0127 mm, Campbell Scientific Inc.,		
	Logan, Utah, USA)		
Volumetric water content (m <sup>3</sup> m <sup>-3</sup> )	2 x water content reflectometer (CS616,		
	Campbell Scientific Inc., Logan, Utah, USA		
Wind speed (ms <sup>-1</sup> ) and direction	Wind Monitor-AQ, model 05305 (R.M.		
(degrees)	Young Company, Michigan, USA)		
Air Pressure (kPa)	CS106 Barometric pressure sensor		
	(Campbell Scientific Inc., Logan, Utah,		
	USA)		

Table 6.2. Bio-meteorological sensors at the Somerton and Truro farm sites.

The LAS and micro-meteorological station sensors were connected to a CR3000 data logger (Campbell Scientific Inc., Logan, Utah, USA) for data recording. Data were saved onto a 2 GB compact flash memory card with the capacity to store up to six weeks of high frequency (20 Hz) data. The LAS transmitter and receiver were powered by two solar panels (SDT800 - 12V

80W Solar Module) that charge four 100 AmpHour deep cycle batteries (Deltec - SMF 1250 High Cycle).

#### 6.4.6 Meteorological data

In order to apply the PML and PMP, meteorological variables required include solar radiation, air temperature, relative humidity (RH), wind speed and rainfall (Table 6.3). These were obtained from a scientific grade Agricultural Research Council AWS located 500 m away from the experimental site at Somerton farm and the same weather station data was used to force the PML and PMP at Truro farm approximately 14 km away. To determine the utility of sparsely distributed weather stations in modelling ET, this study applied meteorological data from the AWS instead of that from the LAS system. It should be noted that in South Africa there is a paucity of validation datasets due to the unavailability of ET measurement equipment such as scintillometers on a wide scale. On the other hand, AWS are more available albeit, sparsely distributed. Therefore, the use of completely independent datasets such as AWS in calibrating and running the ET models could be useful in the determination of ET for areas that do not have validation equipment. Details of the derivation of other meteorological data such as atmospheric pressure, vapour pressure and gap filling of meteorological variables are presented in Appendix B. However, at the Truro site, the Tropical Applications of Meteorology Using Satellite Data and Ground-Based Observations (TAMSAT) rainfall data for Africa PML (Maidment et al., 2014; Tarnavsky et al., 2014) was used to drive the since there was no rainfall station close by. In Chapter 8 of this thesis, the Mann-Whitney test showed that the TAMSAT data at Somerton farm was similar to the observed rainfall from the AWS at the site and this increased confidence in the dataset for application in modelling. TAMSAT rainfall is derived from Meteosat thermal infra-red channels based on the identification of convective storm clouds and training against ground-based rain gauge data and it has a fine resolution of 4 km.

Weather parameter	Instrument
Solar radiation (MJ m <sup>-2</sup> )	Pyranometer (LI-200SA*)
RH (%) and Air temperature (°C)	Vaisala HMP60 Temp/Humidity probe
	(HMP60)
Wind speed (m s <sup>-1</sup> ) and direction (degrees)	R.M. Young wind sentry wind set (10FT
	LEAD, Model 03001)
Rainfall (mm)	Te525mm-l Texas Electronics Rain Gage
	0.1MM (0.00394 INCH, TE525mm-L)

Table 6.3. Meteorological data measured at the Agricultural Research Council's automatic weather station and instrumentation at Somerton farm.

# 6.4.7 Wind speed estimation

It should be noted that in agro-meteorology the reference height for wind measurement is 2 m above the ground, an arrangement similar to the AWS used for this study. The PML is sensitive to the aerodynamic components when applied in short canopies and as such wind speed was estimated at the canopy height instead of using wind speed measured at the reference height of 2 m (Allen et al., 2008). The study applied a power law equation described by Manwell et al., (2002) in extrapolating wind speed to different heights. The equation applied is as follows:

$$V_{\chi} = V_2 \left(\frac{h_{\chi}}{h_2}\right)^{\dot{a}}$$
[6.20]

where  $V_x$  is the wind speed at the height to be extrapolated i.e.  $h_x$  (canopy height),  $V_2$  is the wind speed recorded by the agro-meteorological stations at 2 m from the ground level i.e. ( $h_2 = 2$  m), and the power law exponent  $\dot{a}$  is the wind shear exponent (Manwell et al., 2002). The power law exponent ( $\dot{a}$ ) was calculated as follows:

 $\dot{a} = (0.37 - 0.0881 \ln V_2) / [1 - 0.0881 \ln (h_2 / hx)]$ [6.21]

# 6.4.8 Determining the fraction of soil evaporation (f) and maximum stomatal conductance $(g_{sx})$

In the grassland, the three methods described in Chapter 5 for determining the fraction of soil evaporation (f) were also applied. These included the  $f_{Zhang}$  (Zhang et al., 2010),  $f_{drying}$  (Morillas et al., 2013) and use of measured volumetric soil water content ( $f_{SWC}$ ) to surface determine f. This entailed the application of equations 5.9 - 5.11 in Chapter 5 of this thesis. In order to successfully apply the  $f_{drying}$  approach, the CLIMWAT database (FAO, 2013) was used to determine daily effective precipitation which was estimated at 1.65 mm for the present study site. To successfully implement the  $f_{SWC}$  approach, the minimum volumetric

soil water content ( $\theta_{min}$ ), was obtained from another study site at eZulu Game Reserve (EGR) or Chapter 4 (Gwate et al., 2016) which had a longer soil moisture observation including during the driest months. This was assumed to be representative since the two sites have similar geology, namely Beaufort Series sandsones of the Karoo Supergroup.

# 6.4.9 MODIS data

#### Leaf area index (LAI)

Located on the Terra and Aqua satellites, the Moderate Resolution Imaging Spectroradiometer (MODIS) provides comprehensive series of global observations of the Earth's land, oceans, and atmosphere in the visible and infrared regions of the spectrum. The study used the LAI derived from MODIS fraction of photosynthetically active radiation/ leaf area index (MOD15A2 fPAR/ LAI) product (Myneni et al., 2002) to drive the PML model. Details of the MOD15A2 product were described in Chapter 5 and the extraction procedure can be found in Appendix C.

# Nadir Bidirectional Reflectance Distribution Function Adjusted Reflectance (NBRDF) product (MCD43B4)

This product provides 1-km reflectance data adjusted using the bidirectional reflectance distribution function (BRDF) of MCD43B1 to model values as if they were acquired from a nadir view. Details for deriving surface albedo were presented in Chapter 5 and Appendix D.

#### 6.4.10 Data analysis

#### LAS data

Essentially, the accuracy of the energy fluxes from a LAS is influenced by the mean height of the LAS MkII optical beam above the surface. For flat surfaces, determining the effective LAS beam height is simple and can be derived from the transmitter and receiver heights (Kipp & Zonen, 2012). However, in the real world, an ideal flat surface is rare and as such EVATION (evapotranspiration) software program v2.5.0.11 (Delft, Kipp & Zonen B.V., Netherlands) was used to determine effective LAS beam height following Hartogensis et al. (2003). A slope profile along the path length was generated from Google EarthPro. From the reference point (transmitter), a total of 11 points that were 50 m apart were identified at Truro farm and their height above sea level were recorded and fed into EVATION to derive effective height. At Somerton farm, the effective height was calculated using only 8 points owing to the shorter path length and flatter terrain. A number of parameters were configured before analysis with EVATION could be done. These included selection of LAS Mk11,  $z_{0m}$  and d. The latter two are an expression for the irregularity of the earth's surface and affect the intensity of mechanical

turbulence and the fluxes of *H*, *LE* and momentum above the surface. Vegetation height was estimated at different locations and times during the experiment in order to derive mean canopy height by measuring representative patches. The  $z_{0m}$  and *d* were determined from the estimated canopy height (h) as 0.1h and 0.66h respectively (Allen et al., 1998). Data were downloaded and analysed using EVATION software (Kipp & Zonen, Delft, The Netherlands). The derived *LE* was then converted into mm per hour to get an estimation of water loss.

#### **Data quality control**

During processing, LAS data were controlled using several quality checks (QC). Data were filtered for low signal (demodulated signal less than 10 mV as per requirements of EVATION software). Data were also filtered out after the unit mis-aligned. The Bowen ratio was also used to reject positive fluxes when it was > 3, since H would be far larger than LE and the latter insignificant. Any data points where the Bowen Ratio ( $\beta$ ) was between -0.05 and 0 were removed, due to instability of the solution for this extreme value range (Rambikur & Chávez 2014). It should be noted that over wet surfaces  $\beta$  is small, < 0.5 and when  $\beta$  > 3 LE is insignificant (Bouin et al. 2012; Kipp and Zonen 2012). In addition, when  $\beta$  is close to -1, i.e.  $(-1.25 \le \beta \le -0.75)$ , *LE* and *H* are assumed negligible (Campbell Scientific, 2005). Data during precipitation events were also excluded. Positive fluxes during periods between 5 am and 6 am with  $u^*$  less than 0.1 ms<sup>-1</sup> were also filtered out to avoid conditions with poorly developed turbulence. Periods with a temperature gradient of less than 0.2°C between the lower and upper air temperature sensors were filtered out to avoid the risk of inaccurate determination of atmospheric stability. Further,  $L_{OM}$  was used to filter out large positive (~1 mm) fluxes on a period of absolute stability as determined by the stability parameter. The physical interpretation of  $L_{OM}$  is that a positive value indicates stable conditions while a negative value indicates unstable convective conditions. The  $C_n^2$  was also used to filter out data with  $\leq 10^{-16}$  m<sup>-2/3</sup> since this is indicative of weak and insignificant atmospheric optical turbulence over shorter ( $\leq 2$ km) optical paths (Tunick, 2003). In addition, the upper scintillation saturation criterion was also considered as a potential basis for rejecting fluxes based on equation 6.22 (Kohsiek et al., 2002; Bouin et al., 2012).

$$C_n^2 < 0.057 \, D^{5/3} L^{-\frac{8}{3}} \lambda^{1/3} \tag{6.22}$$

where D is the beam diameter, L is the pathlength,  $\lambda$  is the scintillometer optical wavelength.

#### **Model calibration**

Average hourly latent heat flux (LE) estimates were converted to ET (mm hr<sup>-1</sup>) and summed into daily totals. These were used to parameterise and validate the models. The PML model requires the calibration of  $g_{sx}$  and the rate of soil drying ( $\dot{\alpha}$ ) parameters. As such, the calibration period spanned from DoY 308 to DoY359 (52 days) and only good quality data was used. Despite that the period was short, varied environmental conditions that represent both growing and non-growing seasons prevailed. The validation period spanned from DoY 21 to DoY 101, 2016 for both the models. With respect to the PML model, parameters,  $g_{sx}$  and  $\dot{\alpha}$ were estimated by optimisation using the *rgenoud* package (Mebane & Sekhon, 2011) in R statistical software (Version 3.1.3) and the script for running the model is presented (Appendix E). The parameter estimation exercise sought to find the values of  $g_{sx}$  and  $\dot{\alpha}$  that minimised the cost function (F) over the optimization period (N):

$$F = \frac{\sum_{i=1}^{N} |E_{est,i} - E_{obs,i}|}{N}$$
[6.23]

where  $E_{est,i}$  is the modelled ET for day *i*,  $E_{obs,i}$  is observed ET for day *i* and *N* is the number of sample days.

It should be noted that due to logistical challenges which could not allow for a long time period of measurements at the Turo site, the PML model was validated using  $g_{sx}$  and  $\dot{\alpha}$  values obtained from the Somerton site. The two sites are 14 km apart and have similar soils and vegetation type (Mucina et al., 2006).

#### Stomatal conductance measurements

At the Somerton site, a Leaf Porometer (Decagon Devices, US/ Canada) was used to measure stomatal conductance at a leaf scale and this helped to compare measured and optimised stomatal conductance values.

### **Models evaluation**

The PML and PMP models were then evaluated using the measured LAS ET data. Willmott (1982) noted that no single model evaluation method can adequately describe model performance and as such it is prudent to use different indices simultaneously. Model performance was evaluated using the root mean square error (RMSE) and both the systematic and unsystematic (Willmott, 1981) components are reported. The study also reports on the RMSE-observations standard deviation ratio (RSR) which gives a measure of what is considered a low RMSE (Moriasi et al., 2007). The mean absolute error (MAE) which is less

sensitive to extreme values than RMSE is also reported as well as the percent bias (PBIAS) to give insights into the tendency by models to over-or-under estimate the fluxes.

The linear regression between the observed and modelled ET was also assessed. Model II simple linear regression using the standard major axis (SMA) method in R statistical software environment (R-3.1.3) was performed. This was found suitable for the study since the two variables of interest were amenable to measurement error (Legendre 2013). The coefficient of determination ( $R^2$ ), the slope and y-intercepts were investigated. Slope and y-intercept of the best fit regression line are indicative of the extent to which the modelled agrees with the observed data (Moriasi et al., 2007).

# Sensitivity analysis

The sensitivity of the PML to the aerodynamic components was assessed using a complete year (2012) of data over the grassland at Cala, near the present study sites. Meteorological data was obtained from an AWS while LAI and albedo were obtained from MODIS. This was achieved by varying the canopy height, height of wind speed measurement and by extrapolating wind speed measured at 2 m down to the canopy height by applying the equation developed by Manswell et al. (2002). Differences in the estimated ET were then recorded for comparison purposes.

#### 6.5 Results

#### 6.5.1 Data availability

The effective height at Truro was 3.83 m while at Somerton it was 3.05 m. The location of the path length (beam) and the underlying surface topography at the two study sites are presented (Fig. 6.2). A total of 39% of the data at Somerton farm was lost mainly due to misalignment of the unit resulting in no or lower signal strength (Udemond < 10 mV) and lower  $C_n^2$  of  $10^{-17}$ m<sup>-2/3</sup> or a no number. With respect to the Truro farm 29% of the data were rejected due to misalignment of the system. 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. Based on equation 6.22, LAS saturation would start at  $C_n^2 > 1.85498*10^{-9}$  and  $9.3334*10^{-10}$  at the Truro and Somerton sites respectively. However, the study did not detect any saturation at either of the sites. The major challenge was misalignment of the system and disturbance by animals.



Figure 6.2. Path length beam and underlying surface topography between the LAS transmitter (TX) and receiver (RX) at: a) Somerton and b) Truro farms.

# 6.5.2 Average meteorological conditions

Average environmental conditions during the calibration period at Somerton and validation at Truro farms are presented (Table 6.4).

Table 6.4. Average daily meteorological conditions during the calibration (Somerton and validation (Truro) periods (mean  $\pm$  standard deviation)

Somerton ( $N = 67$ days)	Truro (N = 29 days)
$19.5 \pm 3$	$18.2 \pm 2.5$
$49.1 \pm 27$	$58.2 \pm 16.3$
$138.5\pm55.4$	$99.3 \pm 35$
$2.74\pm0.6$	$3.3\pm0.78$
$4.8 \pm 1.7$	$4.8 \pm 1.3$
$3.5 \pm 1.3$	$2.23 \pm 1.14$
$1.3 \pm 2.3$	$1.65 \pm 3.1$
$1.1 \pm 0.04$	$0.78\pm0.14$
$0.09 \pm 0.2$	$0.14\pm0.2$
	Somerton (N = 67 days) $19.5 \pm 3$ $49.1 \pm 27$ $138.5 \pm 55.4$ $2.74 \pm 0.6$ $4.8 \pm 1.7$ $3.5 \pm 1.3$ $1.3 \pm 2.3$ $1.1 \pm 0.04$ $0.09 \pm 0.2$

With respect to the Somerton site, the prevailing wind was from between the ENE and E sector (24%) and these were light winds of between  $0.14 - 2.4 \text{ ms}^{-1}$  and maximum wind speed was between 6.12 and 8.14 m s<sup>-1</sup> (Fig. 6.3a). However, the Truro site had stronger winds with maximum wind speed above 12 m s<sup>-1</sup>(Fig. 6.3b). The prevailing wind was from the SE and NE direction and the wind speed ranged from  $0.4 - 4.4 \text{ m s}^{-1}$ .



Figure 6.3. Wind speed (ms<sup>-1</sup>) and wind direction at a) Somerton farm and b) Truro farm during the field campaign.

At both sites, the AET pattern followed that of SWC and reference ET (ET0) was consistently higher than AET (Fig. 6.4).



Figure 6.4. Trends in volumetric soil water content (SWC), reference evapotranspiration (ET0) and actual evapotranspiration (ET): a) Somerton and b) Truro farms.

#### 6.5.3 Parameter estimation and validation at Somerton farm

Optimised  $g_{sx}$  was generally similar for the different parameterisation approaches of the PML equation (Table 6.5). The  $f_{drying}$  approach considered a relatively low  $\dot{\alpha}$  in the study area given its 0 – 1 range (Table 6.5). Measured highest stomatal conductance at the leaf level was 0.0025 m s<sup>-1</sup>.

Approach	$g_{sx}$	ά
fdrying	0.0026	0.10
$f_{zhang}$	0.0025	N/A
f <sub>swc</sub>	0.0023	N/A
Parameter ranges	0.002 - 0.02	0 – 1

Table 6.5. Optimized values for model parameters.

All the PML approaches yielded RMSE that was within 15% of the daily observed ET at Somerton farm (Table 6.6). The average observed ET during validation was  $3.5 \pm 1.3$  mm day<sup>-1</sup>. With respect to PML, the  $f_{drying}$  approach yielded a better model fit with a RMSE of 0.26 mm day<sup>-1</sup> and RSR of 0.26 while the  $f_{zhang}$  performed poorly compared to the other approaches of the PML (Table 6.6). The  $f_{drying}$  and  $f_{zhang}$  approaches of the PML equation tended to overestimate the observed ET. On the other hand the  $f_{swc}$  approach and the PMP tended to underestimate the measured ET respectively as shown by the PBIAS (Table 6.6). The PMP equation had a RMSE of 1.76 mm day<sup>-1</sup> and PBIAS of 67%. Most of the RMSE was unsystematic for the two models (Table 6.6). The MAE for the PML lay between 5 and 10% of the observed daily mean ET while that of the PMP was 50 % of the observed mean ET (Table 6.6).

Statistics	$f_{drying}$	<i>f</i> <sub>zhang</sub>	f <sub>swc</sub>	PMP
MAE (mm)	0.18	0.37	0.34	1.76
RMSE (mm)	0.26	0.48	0.4	1.89
RSR	0.26	0.06	0.41	1.94
PBIAS (%)	-0.63	-4.1	3.33	67
Systematic RMSE (%)	3	20	7.8	33
Unsystematic (%)	9	44	13	74
Daily modelled mean ET	$3.6\pm1.37$	$3.74 \pm 1.59$	$3.44 \pm 1.1$	$1.7\pm0.86$

Table 6.6. Model performance at Somerton farm.

# 6.5.4 Truro site - validation

The field campaign was cut short at the Truro farm owing to logistical challenges and as such, the PML model was validated with values calibrated from the Somerton site since both areas are located on similar environments. The lowest RMSE was obtained with the  $f_{swc}$  approach (0.3 mm day<sup>-1</sup>) followed by the  $f_{Zhang}$  (0.34 mm day<sup>-1</sup>) and finally the  $f_{drying}$  with a RMSE of 0.41 mm day<sup>-1</sup> (Table 6.6). The PMP and the PML equation's  $f_{drying}$  approach tended to underestimate observed ET (Table 6.7). With respect to the PMP and the  $f_{swc}$  approach, the RMSE was essentially systematic while it was unsystematic for the  $f_{drying}$  and  $f_{Zhang}$ approaches (Table 6.7). The average measured daily ET during the validation period was 2.23  $\pm$  0.85 mm and the RMSE for the PML approaches was within 20% of the observed daily ET (Table 6.7). The MAE was lower for the PML compared to the PMP (Table 6.7).

Table 6.7. Models performance at Truro farm ( $f_{drying}$ ,  $f_{zhang}$  and  $f_{swc}$  are the different approaches of the PML).

Statistics	$f_{drying}$	<i>f</i> <sub>zhang</sub>	f <sub>swc</sub>	PMP
MAE	0.21	0.26	0.25	1.38
RMSE	0.41	0.34	0.30	1.45
RSR	0.52	0.77	0.7	3.34
PBIAS	4.2	-1.2	-0.36	68.7
Systematic RMSE (%)	8.4	8	13.4	72
Unsystematic (%)	17	15	10	35
Daily modelled mean ET	$2.13\pm0.6$	$2.24\pm0.66$	$2.23\pm0.63$	$1.31\pm0.46$
(mm)				

#### 6.5.5 Variation in ET

The PML  $f_{drying}$  approach was able to follow the dynamics of measured ET at Somerton although it tended to overestimate ET at the beginning of the validation period resulting in a slightly negative PBIAS (Fig.6.5a). However, at Truro farm it underestimated measured ET although it occasionally overestimated the ET (Fig. 6.5c). A similar pattern was observed with respect to the  $f_{zhang}$  approach which however overestimated ET in both sites (Fig. 6.5a and c). The  $f_{swc}$  approach had an overestimation bias at the Truro site at the beginning of the validation period (Fig. 6.5d). Although the PMP model followed the pattern of observed ET, it however, systematically underestimated ET throughout the validation period (Fig. 6.5a and c). The



tendency of the PML to overestimate ET was pronounced after rainfall events. Soil moisture followed the rainfall pattern at both sites (Fig. 6.5c-d).

Figure 6.5. Daily variation in measured evapotranspiration (LAS ET) and modelled ET: a) Somerton farm (PML  $f_{drying}$ , PML  $f_{zhang}$ , PML  $f_{swc}$  and PMP ET models), b) Daily variation in rainfall and volumetric soil water content (SWC) at Somerton farm, c) Daily variation in measured evapotranspiration (LAS ET) and modelled ET at Truro farm (PML  $f_{drying}$ , PML  $f_{zhang}$ , PML  $f_{swc}$  and PMP ET models) and d) Daily variation in rainfall and volumetric soil water content (SWC) at Truro farm.

Data from the two sites were combined and regression equations of the modelled ET against observed ET were developed for each site by summing up 8-day ET (N = 15, 8-day periods) in line with the availability of the MODIS LAI. The linear regression between modelled ET and observed ET was significant for all approaches (p < 0.001). Higher slopes were obtained using the  $f_{drying}$  and  $f_{zhang}$  approaches (Fig.6.6a-b). When data from the two study sites were combined, the  $f_{drying}$  approach yielded a slope of 1 and an intercept of 0.58 mm ( $\mathbb{R}^2 = 0.91$ , Fig. 6.6a). The  $f_{zhang}$  and the  $f_{swc}$  approaches had similar  $\mathbb{R}^2$  although their slopes were different (Fig. 6.6b-c). The lowest  $\mathbb{R}^2$  and slope were observed from the PMP (Fig. 6.6d).



Figure 6.6. Relationship between observed and modelled ET for the two study sites (combined data) with 95% confidence limits.

# 6.5.6 Sensitivity analysis

Canopy height, wind speed and height of wind speed measurements help to define aerodynamic conductance  $(G_a)$ . It is shown that variation in these  $G_a$  components has serious consequences on the PML modelled ET (Table 6.8). In particular, the wind speed at canopy height greatly influences the ET. Therefore, the model can easily overestimate or underestimate ET if the

canopy height, the height of wind speed measurement and the wind speed at canopy are not properly defined.

Canopy height (m)	Height of wind speed measurement (m)	Total ET (mm)
0.12	2	1158.7
0.5	2	1025.6
0.5*	2	572.3
0.5**	0.5	451.7

Table 6.8. Model sensitivity to aerodynamic components at Cala (January –December 2012).

#### Key

\*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) was used.

### 6.6 Discussion

### 6.6.1 Data quality

Although there has been significant development in methods of measuring ET such as scintillometry, ET modelling remains relevant due to a paucity of measured data across the landscape. Good quality data is crucial for model calibration and validation. Hence, the study applied well established and rigorous data quality control protocols in order to accurately derive fluxes (Campbell Scientific, 2005; Bouin et al., 2012; Rambikur & Chávez, 2014). It is envisaged that the data rejection criteria adopted helped to reduce uncertainties in the calculated ET. This enhanced the accuracy and validity of the calibration and validation results. The good performance of the PML model on the Truro farm where only validation was done using calibrated values of  $\dot{\alpha}$  and  $g_{sx}$  from the Somerton site suggests the obtained values could be representative of dynamics at the study sites. In addition, environmental conditions such as SWC and  $R_n$  were also different during the calibration and validation periods and this suggests that the optimised values could be accurate. Although, there were isolated high pulses of AET, generally the atmospheric demand for moisture was high at the study sites as they both evaporated at less than the ET0 level for most of the time and hence, the areas were water limited.

#### 6.6.2 Calibrated model parameters

The estimated values of  $g_{sx}$  were similar for the three approaches for parameterising conductance, indicating convergence in the methods. The  $g_{sx}$  values were slightly lower than the optimised values obtained by Leuning et al. (2008) in Kendall, USA who obtained a value of 0.0048 m s<sup>-1</sup> over a grassland but the observed values were within the limits reported by Kelliher et al. (1995). However, the study also measured stomatal conductance at a leaf scale using a porometer in the study area and the highest measured value was 0.0025 m s<sup>-1</sup>. Stomatal conductance is influenced by a number of factors such as plant nutrition (Schulze et al., 1994), size and stomata density (Liu & Osborne, 2014). It is well established that the dominant species at Somerton (Themeda trianda) and at Truro farm (E. curvula) have evolved to survive in semi-arid areas by reducing stomatal conductance in order to optimise water use (Snyman et al., 2013; Favaretto et al., 2015). In addition, C4 grasses similar to those at the study sites have relatively small stomata, regardless of density, resulting in a lower maximum stomatal conductance to water vapour (Liu & Osborne, 2014). Hence, a combination of these factors and the size of the crop (average height of 0.15 - 0.25 m) could explain the relatively low optimised  $g_{sx}$ . The  $\dot{\alpha}$  was low (0.1) and this may be due to the high SWC since calibrations was done during a wet periodd

#### 6.6.3 Performance of the PML

The  $f_{drying}$  approach outperformed the other PML approaches and the PMP model in reproducing ET dynamics. However, the slight over prediction by the  $f_{drying}$  was due to the higher f values considered by model owing to relatively high precipitation during the validation period at the Somerton site. On the other hand, there was only a few rainy days during validation at Truro, resulting in lower f values and hence the slight underestimation by the model at this site. This is also true with respect to the  $f_{zhang}$  approach although it still overestimated ET at the Truro farm site. This was consistent with Morillas et al. (2013) who also observed that when applied on a daily time stamp, the  $f_{zhang}$  approach tended to over predict ET especially after rainfall events. Although good results were obtained, Zhang et al. (2016) also reported slight overestimation of ET by the  $f_{zhang}$  PML approach. The good performance by the  $f_{zhang}$  approach suggests that it is a robust method capable of reproducing dynamics in ET. Therefore, the method could be useful and inadvertently reduce the number of parameters to be determined in the PML model. This is important especially in data scarce areas as is the case with the present study sites. The slight underestimation of ET by the  $f_{swc}$ at Somerton farm could be linked to errors associated with rescaling volumetric soil water content to *f* values. Despite this, there was good agreement between the observed and predicted ET in both sites from the  $f_{SWC}$  approach. With respect to the three approaches of the PML, most the RMSE was unsystematic and this is a hallmark for good models (Willmott 1981; Leuning et al. 2008). Overall, the RMSE and MAE for the different PML approaches were significantly low relative to mean daily measured ET and this suggests that the model was quite robust. Morillas et al. (2013) found R<sup>2</sup> of 0.24 – 0.59 using different approaches of the PML while this study obtained higher R<sup>2</sup> from the model. Although  $\dot{\alpha}$  was kept constant, reasonably good results were still obtained. It should be noted that in reality  $\dot{\alpha}$  is dynamic since it is influenced by changing environmental conditions, a fact also recognised by Leuning et al. (2008) and Morillas et al. (2013).

#### 6.6.4 Performance of the PMP

The PMP did not perform well in both sites and this shows that scaling ET0 to AET through MODIS LAI may not be adequate in areas with low LAI. It is well established that at low LAI (<2.5),  $E_s$  could be as high as 80% of the total flux (Ventura et al., 2006; Leuning et al., 2008; Mu et al., 2011; Morillas et al., 2013). In addition, short canopies may not be effective in attenuating energy through the canopy to the soil surface and this could have resulted in high energy available at the soil surface  $(A_s)$  to drive  $E_s$ . The LAI in the study area was < 2 and as such the PMP model could not capture the dynamics in ET. Hence, the model systematically underestimated ET owing to the low scaling factor. As a result there was a lot of scatter around the line of best fit owing to the influence of  $E_s$ . It should be noted that the MODIS LAI product is only provided every 8 days yet the grassland responds very rapidly to rain events, and the delay in acquiring the latest LAI after the first rain events would have meant that in the first days of validation, model predictions were compromised. Given that the PMP is a parsimonious model forced by readily available data, it is prudent to incorporate  $E_s$  in the formulation in order to improve ET estimation. However, Palmer et al. (2014) found good model fit using the PMP in a semi-arid savanna of South Africa and hence vegetation physiognomic structure could explain these disparities in results.

# 6.6.5 Sensitivity analysis of the PML

When applying the PML it is important to accurately determine aerodynamic components as shown by the sensitivity analysis of the model over the grassland. Results suggest that over short canopies, ET can easily be overestimated if wind speed at the reference height is used. High wind speed is recorded at the reference height of 2 m compared to the actual wind speed at the canopy. The increase in the height of wind speed measurement, results in an increase in the modelled ET. Hence, in areas characterised by short vegetation such as grassland, the estimation of the wind speed at the canopy height is crucial in order to derive accurate fluxes.

# 6.7 Conclusion

Based on the model evaluation metrics, the PML performed better than the PMP model. The PML equation was calibrated in semi-arid grassland and there was good agreement with the measured data. Hence, the calibrated values may be applied across grasslands in South Africa with reasonable confidence. The  $f_{drying}$  outperformed other approaches of the canopy and surface conductance of the PML model and also the single layer PMP model. 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 and this further simplifies the determination of water vapour fluxes. Routine meteorological data were able to reproduce fluxes calculated using micrometeorological methods over this grassland. This means sparsely distributed weather stations can confidently be used to derive reasonable ET over wide areas as the validation exercise revealed. Determining accurate wind speed at the canopy height is crucial when working in short vegetation in order to derive reasonable ET estimates using the PML equation. The inadequacy of the PMP to simulate observed ET in the study area confirmed the importance of  $E_s$  in such environments and therefore, the PMP could be improved by adding a  $E_s$  component as LAI alone was not good enough in constraining ET0 to AET in the study site.

# 6.8 References

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# CHAPTER 7: ESTIMATING EVAPOTRANSPIRATION IN DRYLANDS: SCALING POTENTIAL TO ACTUAL EVAPORATION AND THE ROLE OF SOIL EVAPORATION

This chapter will be submitted to an appropriate journal

OG was part of a small team (OG, ARP and SM) that installed the eddy covariance system in the Albany Thicket and the large aperture scintillometer at the grassland sites. OG assisted with the in-field installation, calculated system parameters for use in the EddyPro® and Evation software, analysed all the water and energy fluxes using EddyPro® and Evation, wrote the manuscript.

# 7.1 Abstract

The escalating world population necessitates the need to understand 'productive' and 'unproductive' water vapour losses. In a context of water scarcity, efforts to increase agricultural production should focus on improving water productivity. This requires an appreciation of the various components of evapotranspiration (ET) including soil evaporation  $(E_s)$ . ET is one of the least understood components of the hydrological cycle. Various complex and simple algorithms have been developed to determine ET. In data scarce areas, developing and testing parsimonious algorithms is useful. This study sought to improve a simple single layer model by incorporating a  $E_s$  component. Empirical methods were also explored to predict ET from vegetation indices (VIs), leaf area index (LAI) and reference evapotranspiration (ET0). A large aperture scintillometer (LAS) and an eddy covariance (EC) system were used to validate the proposed algorithm at three sites over Grasslands and Albany Thicket (AT) biomes in the Eastern Cape, South Africa. There was good agreement between the observed and predicted ET with RMSE of 0.3–0.58 mm day<sup>-1</sup> when average daily observed ET was 0.43– 3.24 mm. Regression of LAI and ET0 against observed ET were significant (p < 0.001). The VIs had moderate correlations with the observed data due to the significant role played by  $E_s$ (65-84%) across the sites and stomatal conductance at the AT site. The simple algorithms developed would make determining ET easier in data scarce regions.

*Keywords:* Albany Thicket, evapotranspiration, grassland, soil evaporation, leaf area index, reference evaporation, vegetation indices

#### 7.2 Introduction

Evapotranspiration (ET) is one of the most important components of the hydrological cycle in terms of global change studies but remains one of the least known variables necessary for better understanding the ecohydrological system. Essentially, ET comprises water loss from various surfaces and transpiration through plant leaves. Transpiration (T) is closely coupled with plant production while  $E_s$  reflects the so-called 'unproductive' loss of water to the atmosphere (Hoff et al. 2010; Kool et al. 2014). As many parts of the world are increasingly becoming water limited the need to account for ET and its various components cannot be overemphasized. More importantly, the increasing world population requires improvements in water productivity especially in water limited environments (Molden et al. 2010; Kool et al. 2014). Therefore, it is prudent to enhance productive water use and reduce the so-called 'unproductive' evaporation. Partitioning of ET into its various components such as  $E_s$ , and T provides a sound

starting point for enhancing water productivity. Consequently, a number of algorithms, ranging from data intense to parsimonious ones exist to account for total ET. In data scarce areas, simple models using readily available input data are useful. Models have been developed that are based on empirical relationships between observed ET and another independent variable such as the LAI or VIs that are known to correlate with ET, for example, the normalised difference vegetation index (NDVI) and the enhanced vegetation index (EVI) (Nagler, et al., 2005a; Nagler et al., 2013; Palmer et al., 2014; Glenn et al., 2015). For broadleaf vegetation, LAI denotes the one-sided green leaf area per unit ground area while in canopies with needle shaped leaves it reflects one half the total needle surface area per unit ground area (Knyazikhin et al., 1999; Myneni et al., 2003). Hence, larger LAI values provide a larger surface area for ET. On the other hand, VIs are based on the premise that reflected energy in the visible wavelength is very low as a result of high absorption by photosynthetically active pigments (Huete et al., 1999). As such in healthy green vegetation, most of the near-infrared radiation (NIR) is scattered while the red spectrum is largely absorbed. As a result, the contrast between red and near-infrared responses is a sensitive measure of vegetation amount, with maximum red-NIR differences occurring over a full canopy and minimal contrast over targets with little or no vegetation (Huete et al., 1999).

Other approaches tend to combine these VIs with other meteorological data such as air temperature and net radiation  $(R_n)$  in simple or non-linear and multiple linear regressions in order to develop predictive equations (see review by Glenn et al., 2008). These empirical relations are very crucial in data scarce areas and where there is no ET validation equipment. In South Africa, there are a relatively few micrometeorological observation towers, although scientific-grade weather stations are increasing in frequency. Therefore, the development of such simple empirical algorithms may be useful in deriving ET for all biomes of the country. The theoretical basis for such empirical algorithms is the recognition that LAI and VI represent vegetation canopy function at a particular place and time as they measure canopy greenness (Knyazikhin et al., 1999; Huete et al., 2002). It is well established that LAI and VI are intricably intertwined to carbon and water vapour fluxes over canopies (Glenn et al., 2008). Hence, dynamics in these phenological attributes is indicative of carbon and water vapour fluxes not withstanding the influence of stomatal conductance. Some vegetation types have evolved to exercise great control over water vapour loss through changing stomatal behviour, the size and density of stomata (Schulze et al., 1994). Such convergent characteristics are important for vegetation found in marginal lands as they enable them to survive periods of moisture deficit.

For example, in South Africa, the AT Biome is characterised by leaf and stem succulence (mainly *Portulacaeae, Euphorbiaceae, Crassulaceae* and *Aizoaceae*), and is believed to have very high water use efficiency, resulting in the widespread environmental plantings of species such as *Portulacaria afra* in order to sequester more carbon (Gwate et al., 2016). This resource optimisation behaviour has been observed throughout the world as vegetation tend to scale their foliage density to match resources availability (Reich et al., 1997; Reich et al., 2003; Zeppel, 2013). Consequently, models have been developed trying to link water vapour fluxes to canopy attributes. These have mainly revolved around connecting potential ET (PET) or reference crop evapotranspiration (ET0) to actual evapotranspiration (AET) by using crop coefficients, or using LAI or VI as scalars (Allen et al., 1998; Nagler et al., 2013; Palmer et al. 2014; Glenn et al., 2015). The empirical relations take the following forms:

$$ET = K_c ET0$$

[7.1]

[7.2]

where  $K_c$  is the crop coefficient and ET0 is the reference evapotranspiration.

Alternatively vegetation indices could be used to connect ET0 to AET whereby the  $K_c$  is replaced by VIs:

ET = f(VI) \* ET0

These approaches of determining ET have been widely applied in crops and natural ecosystems including semi-arid grasslands (Allen et al., 1998; Allen et al., 2011; Glenn et al., 2015). However, there are a number of challenges and uncertainties related to the use of LAI or VIs approaches to determine ET. For example, they are unable to detect changes in stomatal behaviour. The dynamics in stomatal behaviour greatly influence the carbon and water vapour exchanges over canopies which in turn affect the partitioning of total ET into  $E_s$  and T. Kool et al. (2014) reviewed various methods of partitioning ET and robust ET models should be able to discriminate  $E_s$  and T especially in a context where improving water productivity is crucial. Unfortunately, approaches employing LAI and VIs to connect potential ET and actual ET are not able to determine  $E_s$ . However, it is well established that  $E_s$  is significant in drylands with LAI < 2.5 and can contribute ~ 80% of total ET (Leuning et al., 2008; Mu et al., 2011; Morillas et al., 2013). Therefore, in such systems, there is a need for algorithms that can also capture  $E_s$  in order to accurately characterise total ET.

The main aim of this study was to explore improved model formulations over the grasslands and Albany Thicket vegetation by advancing the preliminary work of Palmer et al. (2014), conveniently called the Penman-Monteith-Palmer (PMP) algorithm. Palmer et al. (2014) reckoned the need for developing and testing parsimonious ET models in data scarce areas such as southern Africa and ET was successfully estimated at a semi-arid savanna site using routine meteorological data and the LAI. This study adds a  $E_s$  component to the preliminary work of Palmer et al. (2014) in order to improve ET estimation in drylands characterised by short and open canopies. The proposed algorithm has the advantage of using widely available weather data, surface albedo as well as LAI and it does not require observed ET in order to calibrate some parameters and this is crucial in data scarce areas. Secondly, this study sought to develop simple empirical algorithms for predicting ET in such environments using observed ET on one hand and ETO as well as LAI on the other. Such empirical relations may help in scaling up ET from point observations to the landscape across the biomes of interest.

### 7.2.1 Theory

Based on the resource optimisation theory (Glenn et al., 2008; Zeppel, 2013), plants have evolved to scale foliage density in line with resources availability. Hence during optimum conditions, canopy attributes such as the LAI are well developed and possibly capturing more CO<sub>2</sub> in exchange for water vapour. However, stomatal conductance and other environmental conditions will also modulate these exchange processes. Hence, in vegetated surfaces, AET approaches PET or ET0 under ideal conditions of plentiful soil moisture and soil fertility when plant root systems are able to supply water to the atmosphere via stomata at a rate almost corresponding to demand. The model uses LAI as a scalar to connect AET with ET0. Details of the PMP model can be found in Palmer et al. (2014) and were also presented in Chapter 6 (equation 6.1).

This study proposes the addition of a  $E_s$  component on the original single layer algorithm described by Palmer et al. (2014). Modelling  $E_s$  is quite a delicate issue since a good model should be able to reproduce the rate of soil moisture changes over time. However, it is well established that the link between ground water and the upper soil moisture is one of the least understood hydrological process (Wilcox, 2010) and this exacerbates the problem. It is recognised that the rate of  $E_s$  follows three stages as a result of soil physical and atmospheric characteristics (Kool et al., 2014). Stage 1 denotes a period where  $E_s$  is limited by available energy (A) in the upper layers of the soil and stage 2 where water loss is strongly coupled with soil characteristics such as soil moisture, soil hydraulic properties and vapour pressure deficit. Stage 3 relates to a context where  $E_s$  is dependent on heat flux from a relatively dry soil (Hulugalle et al., 2017). In order to capture these dynamics, the ratio of equilibrium evaporation to precipitation method was adopted (Zhang et al., 2010; Morillas et al., 2013) after its successful implementation in Chapters 5 and 6 of this thesis. Many studies have demonstrated that this approach was able to capture the soil drying process (Morillas et al., 2013; Zhang et al., 2010, 2016). The approach has the advantage that it simply uses rainfall and equilibrium evaporation data to parameterise the fraction (f) of  $E_s$  and there is no need for parameter fine tuning. Therefore, such simple models are relevant in data scarce areas and can be used with sparsely distributed weather stations to enable accounting for ET. The proposed improved algorithm is essentially driven by meteorological data, surface albedo and the LAI and is presented as:

$$ET = \frac{LAI}{LAI_{max}} * ET_0 + f \frac{\varepsilon A_s}{\varepsilon + 1}$$
[7.3]

where  $A_s$  is energy available to the soil,  $LAI_{max}$  is maximum leaf area index,  $\varepsilon$  is slope ( $\Delta$ ) of the curve relating saturation water vapour pressure to temperature divided by the psychrometric constant ( $\gamma$ ), f is a factor modulating potential evaporation from the soil and it ranges between 0-1.

For the *f* value, the study adopted the precipitation and equilibrium evaporation ratio method conveniently called the  $f_{Zhang}$  (Zhang et al., 2010; Morillas et al., 2013):

$$f_{Zhang} = \min\left(\frac{\sum_{i=15}^{i} P_i}{\sum_{i=15}^{i} E_{eq,s,i}}, 1\right)$$
 7.4]

where  $P_i$  is the accumulated daily precipitation and  $E_{eq,s,i}$  is the daily soil equilibrium evaporation rate for day *i* over a number of days (N) and this study used N = 16 days (day *i* and 15 preceeding days).

NB: The logistics for deriving soil available energy  $(A_s)$  were described in Chapter 5 of this thesis (equations 5.1 - 5.7).

#### 7.3 Material and Methods

# 7.3.1 Study site

Three study sites were selected for testing and validating the algorithm. These included two sites in the grassland biome, one in the Southern Drakensberg Highland Grassland (Truro farm) and the other in the East Griqualand Grassland (Mucina et al., 2006) i.e. Somerton farm in the north Eastern Cape province, South Africa (Fig. 1, Table 7.1). The two grassland sites are situated approximately 14 km apart on freehold land where mixed farming is practiced. Extensive cattle and sheep production as well as rainfed crop cultivation are key farming activities. The third study site is situated in the Great Fish Thicket in the Albany Thicket (AT) Biome on the eZulu Game Reserve (EGR) in the south western Eastern Cape. The succulent
Thicket vegetation at this study site has been used to support extensive livestock farming (sheep and goats) since the early 1800s and has recently (circa 1998) been converted to wildlife ranching. There is no dryland crop cultivation, but irrigated cultivation does occur along the Great Fish River.



Figure 7.1. Location of study sites (eZulu Game Reserve, Truro and Somerton farms).

Table 7.1. Location a	and	characterist	tics of	study	sites.
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Site name	Lat/ Lon	ET data period	Instrument	Vegetation type	Elevation	*MAR
					(m)	(mm)
Somerton	31° 9'2.00"S,	DoY 309, 2015-	LAS	East	1257	756
	28°23'3.00"E	DoY 101, 2016		Griqualand		
				Grassland		
Truro	31° 4'10.03"S,	DoY 265-DoY	LAS	Southern	1471	786
	28°17'25.05"E	308, 2015		Drakensberg		
				Highland		
				Grassland		
eZulu	33° 01'	DoY 283, 2015-	EC	Great Fish	554	400
Game	08.929" S, 26°	DoY 318, 2016		Thicket		
Reserve	04' 47.860" E			(Albany		
(EGR)				Thicket biome)		

\*Mean annual rainfall (mm).

# 7.3.2. Data

# Measurement of ET and micrometeorological variables

At the EGR site, ET was measured by an Integrated CO<sub>2</sub>/H<sub>2</sub>O Open-Path Gas Analyser and 3D Sonic Anemometer (IRGASON, Campbell Scientific Inc., Logan, Utah, USA) EC system and details of data analysis are presented in Chapter 4 (Gwate et al., 2016). The EC directly measures latent heat flux (LE) and sensible heat flux (H). At the grassland sites a LAS (LAS, LAS MkII, Kipp & Zonen BV, Delft, The Netherlands) was used for validating the new algorithm. Details of instrumental set up, data processing and quality checks were presented in Chapter 6.

# Meteorological data

Routine daily meteorological data in the form of air temperature, relative humidity (RH), solar radiation ( $R_s$ ), wind speed and rainfall were obtained from an automatic weather station (AWS) in order to derive ET0 and  $A_s$ . At Truro farm, there was no weather station and as such the Agricultural Research Council's Somerton station was used which was approximately 14 km away. This enabled the study to test the utility of sparsely located weather stations in ET estimation over wide areas. However, a rainfall dataset combining ground and remotely sensed data called Tropical Applications of Meteorology Using Satellite Data and Ground-Based Observations (TAMSAT, Maidment et al., 2014; Tarnavsky et al., 2014) was used in the calculation of the *f* values at the Truro farm site since there was no weather station. Chapter 8 of this thesis has proven that TASMSAT rainfall data was similar with that from an AWS at Somerton farm. A summary of instrumentation for the weather station at the Somerton farm and EGR sites is presented (Table 7.2). Further details for deriving other meteorological data can be found in Appendix B.

Weather parameter	Instrument
Solar radiation (MJ m <sup>-2</sup> )	Pyranometer (LI-200SA*)
RH (%) and Air temperature(°C)	Vaisala HMP60 Temp/Humidity probe (HMP60)
Wind speed (m s <sup>-1</sup> ) and direction	R.M. Young wind sentry wind set (10FT LEAD,
(degrees)	Model 03001)
Rainfall (mm)	Te525 mm-l Texas Electronics Rain Gage 0.1MM
	(0.00394 INCH, TE525 mm-L)

Table 7.2. Summary of instruments at the automated weather station.

# MOD 15A2 FPAR/ LAI product

The MODerate-resolution Imaging Spectroradiometer (MODIS) provides 1 km spatial resolution data every day in 36 spectral bands and these have been used to develop several products. The MOD15A2 (FPAR/ LAI) product was acquired from the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) website (https://lpdaac.usgs.gov/dataset discovery/modis/modis products table/mod15a2) and subsequently extracted the 8-day LAI for the three areas of interest from the year 2000 to day of year (DoY) 318 in 2016. This provided the LAI values used in the algorithm (equation 7.3 above) to derive the ET. Details of LAI extraction are provided in Appendix C.

### **MODIS vegetation indices (MOD13A2)**

Vegetation indices (VIs) are empirical measures of vegetation performance and include NDVI and EVI. VIs are essentially indicative of the integrative functions of a vegetated surface (Huete et al., 1999; Huete et al., 2002). The 16-day MOD13A2 product with a spatial resolution of 1 km was also used during this study and it was acquired from the ORNLP DAAC website (https://lpdaac.usgs.gov/data\_access/data\_pool) and NDVI and EVI values coinciding with the study period were extracted. The NDVI is a normalized transform of the NIR to red reflectance ratio, designed to standardize VI values to between -1 and +1 and is expressed as:

$$NDVI = \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}}$$
[7.5]

The EVI is an improvement on NDVI and it incorporates an algorithm to reduce the effects of atmospheric scattering, canopy background reflection and does not saturate in high biomass areas as opposed to the NDVI (Huete et al., 2002). The EVI formula is expressed as:

$$EVI = 2.5 \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + 6\rho_{red} - 7.5\rho_{blue} + 1}$$

$$[7.6]$$

where  $\rho_x$  is the full or partially atmospheric-corrected (for Rayleigh scattering and ozone absorption) surface reflectance.

# Nadir Bidirectional Reflectance Distribution Function Adjusted Reflectance (NBRDF) product (MCD43B4)

The MCD43B product (Strahler & Muller, 1999) was used to obtain the surface albedo. This product provides 1 km reflectance data adjusted using the bidirectional reflectance distribution function (BRDF) of MCD43B1 to model values as if they were acquired from a nadir view (Strahler & Muller, 1999). The MODIS BRDF/Albedo product combines registered, multi-date, multi-band, atmospherically corrected surface reflectance data from the MODIS and Multi-angle Imaging SpectroRadiometer (MISR) instruments to a BRDF in seven spectral

bands at a 1 km and 8 day temporal resolution. Short wave albedo is required in the calculation of net radiation ( $R_n$ ) when the new algorithm is applied. Hence, the MCD43B4 product was acquired from the ORNL DAAC web site (https://lpdaac.usgs.gov/data\_access/data\_pool) and extracted the average 8-day albedo values that coincided with the study period. Subsequently, equation 5.12 in Chapter 5 was applied to compute surface albedo. The script for extracting and computing surface albedo can be found in Appendix D.

### 7.3.3 Model evaluation

The mean absolute error (MAE) and root mean square error (RMSE) were chosen as metrics to evaluate the new algorithm. These indices indicate the extent of the error in the simulated and measured ET and they have the advantage of using units similar to variables under consideration. The MAE is suitable for uniformly distributed errors as it gives the same weight to all errors while the RMSE gives errors with larger absolute values more weight, and hence it is necessary for evaluating data that are normally distributed such as model errors (Chai & Draxler, 2014). Therefore, it is important to report both of these error indices in model evaluation. The RMSE-observations standard deviation ratio (RSR) which standardizes RMSE using the observations standard deviation was also used in order to give insights as to what should be considered as low RMSE (Moriasi et al., 2007). The percent bias (PBIAS) was also computed to help decipher model over-and under-estimation bias. Finally, simple linear regression using the ordinary least square (OLS) regression method was prepared between the observed and predicted. The R<sup>2</sup>, slope and intercept of the linear regression between the observed and modelled were also reported. These were chosen since they are reflective of the extent to which simulated ET reproduces the measured ET while the R<sup>2</sup> shows the proportion of variance in measured ET that is explained by the model (Moriasi et al., 2007).

### 7.3.4 Development of predictive equations

Vegetation indices have been widely used to predict ET over wide areas (Nagler et al., 2005b; Glenn et al., 2010, 2015; Nagler et al., 2013). Data from the two grassland sites were combined and the EGR data was used separately in developing regressions to explore the possibility of estimating ET in these biomes using VIs, LAI and ET0. Simple linear, nonlinear regression and the linear correlation (r) of VIs (NDVI and EVI) against ET were also generated in order to explore the degree of collinearity between the observed ET and VIs. In this case 16-day ET was summed in order to coincide with the availability of VI. This relationship enabled the study to make a determination as to whether VIs can be used to predict ET in environments similar

to the study site. Furthermore, multiple linear regressions of measured ET0 and LAI against ET were developed for the grassland and the AT sites respectively in order to develop simple algorithms for estimating ET in data scarce areas.

# 7.4 Results

### 7.4.1 Environmental characteristics across the study sites

The environmental conditions varied greatly at each experimental site (Table 7.3). 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. RH 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. Mean daily rainfall for Somerton site was 42 and 76% greater than at the Truro and EGR sites respectively (Table 7.3). The average volumetric soil water content (SWC) pattern was in sync with the rainfall and the lowest SWC 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 (Table 7.3).

Environmental	Somerton ( $N = 104$ )	Truro (N = 29)	EGR (N = $401$ )
parameter			
 Air temperature (°C)	$20.22 \pm 3.68$	$18.2 \pm 2.5$	$19.5 \pm 4.7$
Relative humidity (%)	$67.5 \pm 29.4$	$58.2 \pm 16.3$	$62.24 \pm 12.84$
Wind speed (ms <sup>-1</sup> )	$1.41\pm0.37$	$3.2\pm0.78$	$1.73\pm0.75$
Net radiation (W m <sup>-2</sup> )	$127.3 \pm 55.6$	$99.3\pm35$	$71.8\pm52$
ET (mm)	$3.24 \pm 1.24$	$2.23\pm0.85$	$0.76\pm0.65$
ET0 (mm)	$4.5 \pm 2.1$	$4.8 \pm 1.3$	$3.24 \pm 1.48$
SWC (m <sup>3</sup> m <sup>-3</sup> )	$0.22 \pm 0.11$	$0.14\pm0.02$	$0.09\pm0.02$
Rainfall	$2.95\pm5.86$	$1.7 \pm 3.2$	$0.78\pm2.5$
LAI $(m^2 m^{-2})$	$1.32 \pm 0.23$	$0.77\pm0.14$	$0.39\pm0.14$

Table 7.3. Environmental conditions during the experiments (mean  $\pm$  standard deviation).

# 7.4.2 Model performance

The improved PMP algorithm resulted in a RMSE of 0.58 mm day<sup>-1</sup> at Somerton and 0.39 mm day<sup>-1</sup>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 0.5 mm day<sup>-1</sup>and this was largely unsystematic (Table 7.4) in a context of a daily mean of 0.76 mm. The average daily observed and modelled ET was similar over the grassland sites but it differed by 18% at EGR. The RSR was similar across sites (0.08 – 0.13) (Table 7.4). The model tended to slightly overestimate and underestimate observed ET at the Truro and Somerton sites respectively as shown by the PBIAS (Table 7.4). The unsystematic RMSE was relatively higher than the systematic RMSE across the sites. When data from the two grassland sites were combined the RMSE was within 18% of the observed mean daily ET (3.01  $\pm$  1.23 mm) against the modelled of 3  $\pm$  1.55 mm (Table 7.4). Modelled soil evaporation accounted for 69, 65 and 84% of the total modelled ET at Truro, Somerton and EGR respectively.

Statistics	Somerton	Truro	Grassland	EGR
			Combined	
MAE	0.50	0.19	0.45	0.32
RMSE	0.58	0.39	0.55	0.5
RSR	0.08	0.11	0.08	0.13
PBIAS	0.11	-0.38	0.04	-2.6
Systematic RMSE	20	14	24	18
Unsystematic RMSE	31	13.5	31	63
Mean $\pm$ SD modelled ET	$3.21 \pm 2.7$	$2.28\pm0.62$	3 ± 1.55	$0.9 \pm 0.77$

Table 7.4. Model evaluation at Somerton farm (N = 104 days), Truro farm (N = 29 days) and EGR (N = 401 days).

At the EGR the growing (August-April) and non-growing season (May-July) RMSE were 0.51 and 0.3 mm day<sup>-1</sup> respectively and the PBIAS was negative for both seasons (Table 7.5). In the non-growing season the average EC ET was  $0.43 \pm 0.49$  while in the growing season it was  $0.85 \pm 0.66$ .

Table 7.5. Model performance in summer (N = 312 days) and winter (N = 89 days) at EGR.

Statistic	Summer	Winter
MAE	0.30	0.23
RMSE	0.51	0.30
RSR	0.13	0.08
PBIAS	-2.3	-2.5
Systematic RMSE	19	22
Unsystematic RMSE	58	61
Mean $\pm$ SD modelled ET	1.03±0.8	$0.45\pm0.38$

At the Somerton site, the improved algorithm underestimated ET at the beginning of the calibration period but intermittently over estimated ET after DoY 21, 2016. The model also underestimated ET between DoY 89 and 94 (Fig 7.2a-b). A similar pattern was observed at the Truro farm (Fig. 7.2c-d). The underestimation coincided with periods of reduced rainfall while the overestimation bias occurred during periods after rainfall events. A similar pattern was observed at the EGR site (Fig. 2.1e-f).



Figure 7.2. Variation in measured ET, modelled ET and rainfall at a-b) Somerton Farm, c-d) Truro farm and e-f) eZulu Game Reserve (EGR).

The linear regression between the observed and modelled ET were significant (p < 0.001). The combined grassland dataset yielded a slope of 1.04 ( $R^2 = 0.73$ ) while at the EGR site a slope of 1.02 was obtained ( $R^2 = 0.52$ ). At both sites there was no positive autocorrelation (p > 0.05). When the EGR data was separately analysed by seasons, a slope of 1.02 and intercept of 1.1 mm were obtained for the growing season ( $R^2 = 0.49$ ). For the non-growing season, a slope of 0.92 and intercept of 1.1 mm ( $R^2 = 0.49$ ) were obtained. The scatter plots of the relationships

between the observed and predicted ET over the entire validation periods for the grasslands and EGR sites are presented (Fig. 7.3). The ET data was accumulated over 8-day periods to coincide with each new MODIS 8-day LAI.



Figure 7.3. Relationship between a) accumulated 8-day observed ET from the large aperture scintillometer (ET LAS) and the improved algorithm over the grassland (N = 20, 8-day periods) and b) accumulated 8-day observed ET from the eddy covariance system (ET EC) and the improved algorithm over the Albany Thicket (N = 51, 8-day periods).

# 7.4.3 Predicting ET from Vegetation indices and LAI

Using linear and nonlinear regression, the relationship between VIs and ET was weak ( $R^2 \le 0.3$ ). The study found a relatively moderate correlation between ET and VI at the study sites (Table 7.6). However, NDVI had a better correlation with ET (p < 0.05) while the relationship between EVI and ET was insignificant at EGR (p > 0.05). NDVI was better correlated with ET than EVI across the sites (Table 7.6).

Study site			EVI	NDVI
Somerton	and	Truro	0.47	0.53
farm				
EGR			0.31	0.47

Table 7.6. Correlation coefficients between ET and vegetation indices.

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:

ET = 16 * LAI + 0.004 * ET0 - 0.17	[7.7]
Using the combined data from the grassland sites, significant re	lationships were also found (R <sup>2</sup>
= 0.65, $F = 16.73$ , p < 0.001, N = 20, 8-day periods) and the eq	uation was:
ET = 14.19 * LAI + 0.58 * ET0 - 14.1	[7.8]

### 7.5. Discussion

### 7.5.1 Validity of observed ET

This study sought to advance the work of Palmer et al. (2014) in order to accurately estimate total ET in drylands. Although the two grassland sites were adjacent to each other, environmental conditions differed during the respective validation periods. Owing to the field campaign approach adopted and logistical constraints, micrometeorological measurements could not be conducted across the growing and non-growing season over the grassland sites. Suffice to note that rainfall predominantly occurs during the growing season months in the grasslands study sites and much of ET takes place during this period. The data collected were essentially for the wet growing season although environmental conditions varied. For the EGR site, data were collected for an entire year and as such the experiment captured the seasonal water vapour fluxes over the study area. The environmental conditions at the grassland sites and the EGR site were different. For example, long-term modelled mean annual rainfall are 756 – 786 and 400 mm per year at the grassland and the EGR sites (Schulze, 1997) respectively. Therefore, the validation took place under varied environmental conditions and the improved model was largely able to capture the dynamics of ET as measured using a LAS and EC. The underlying assumption is that these micrometeorological methods are measuring the actual ET at the study sites. In addition, uncertainties associated with the inputs especially MOD15A2 LAI and MCD43B surface albedo may have influenced the fluxes derived. For example, errors in the MOD15A2 LAI introduce uncertainties in the modelled ET and the tendency by MOD15A2 LAI to overestimate LAI by up to 0.25 units, has been recognised (Huemmrich et al., 2005). The stability of SWC is connected to the bimodal nature of the rainfall pattern and possibly the intricate link between ground water and soil moisture as well as the convergent evolution of vegetation associated with high water storage capacity.

#### 7.5.2 Model performance and evaluation

The model performed better over grassland as shown by the RMSE but the RSR was low across the grassland and AT, suggesting that the model simulation was good in both biomes. At the grassland sites, validation was done during a generally wet period and the improved model was

largely able to reproduce these dynamics. However, the underestimation bias at the beginning of the validation period could possibly be due to low modelled SWC. The tendency to overestimate ET at the EGR site was due to overestimated  $E_s$  and possibly the underestimated LE as shown by poor energy balance closure in Chapter 5. In addition, the LAI that is used to connect ET0 to T in the model was relatively stable. However, in the AT on the EGR it is suggested that the dominant shrub, P. afra, exercises greater stomatal control, resulting in high water use efficiency (Mills & Cowling, 2006; Gwate et al., 2016). Admittedly, grasslands may also exercise great stomatal control over ET (Snyman et al. 2013; Favaretto et al. 2015) but the 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 & Cowling, 2006; Gwate et al. 2016). Therefore, the available leaf area is not necessarily reflective of ET taking place as changes in stomatal behaviour greatly influence the water vapour flux. This result was not surprising since the LAI which represents the phenological characteristics of the vegetation in the model cannot detect variations in stomatal behaviour which influence the total flux over vegetated surfaces. 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 is also 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 has shown that increasing N reduces overestimation and the optimum N lies between 16 and 20 days (Morillas et al., 2013). However, 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). Willmott (1981) warned that models that had a relatively high systematic RMSE were not good enough and should not be accepted despite seemingly good fit. Therefore, the results from this study confirm that the improved algorithm is robust. 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 fluxes 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. This work, therefore, has advanced the preliminary work by Palmer et al. (2014) to develop parsimonious models for predicting ET in data scarce areas at a fine resolution.

### 7.5.3 Predicting wide area ET from VIs

In line with the objective of developing simple algorithms for estimating ET in drylands where data is scarce, the relationship between VIs and ET were investigated. Relatively moderate positive correlations between ET and VIs were observed. However, across sites, NDVI had better correlations with measured ET than EVI. These results were consistent with those of Haynes & Senay (2012) who found even lower correlations of 0.14 during the winter season in the USA. In addition, Helman et al. (2015) found that NDVI provided better model fit than EVI when VIs were regressed against observed ET in the Mediterranean regions. However, the moderate correlations were in sharp contrast with results from the USA that found EVI to be a more useful scalar in connecting potential ET to actual ET (Nagler et al., 2005a; Nagler et al., 2007; Glenn et al., 2008). The moderate correlations in the present study sites were due to the low VIs and LAI (0.1 – 1.8). It is well established that in areas with LAI  $\leq$  2.5,  $E_s$  is crucial and could account for ~ 80% of total evaporation (Leuning et al., 2008; Morillas et al., 2013; Mu et al., 2007). At the same time, VIs cannot either estimate  $E_s$  or dynamics in stomatal conductance (Glenn et al., 2010). Therefore, results from this study are not surprising since  $E_s$ accounted for between 65 - 84 % of total ET across sites. This is consistent with literature values of between 30 - 80 % reported in rangelands (Kool et al., 2014). So the moderate relationship was caused by the influence of  $E_s$  and stomatal control of ET in the study sites. Owing to these moderate relations, the study could not go on to develop predictive equations. Hence, the objective of developing robust but simple algorithms using VIs was not successful.

However, robust relations were developed through multivariate regression of ET0 and LAI against measured ET. The R<sup>2</sup> at EGR was relatively lower due to the great stomatal control of the ET process. Therefore, the study succeeded in further developing simplified algorithm since credible strong relations were developed. These algorithms may be used to predict biome specific ET, an approach that is becoming common in ecohydrological studies (Fang et al., 2016). The strong relationships developed are crucial particularly for South Africa over the AT since this biome is critical in global change studies owing to its perceived high water use efficiency. This makes the task of estimating ET in such drylands easier by simply using ET0 and LAI in the empirical relationship developed in this work. However, such algorithms need further validation.

### 7.5.4 Model uncertainties

The study improved the PMP by introducing a  $E_s$  component, making it a two layer model. Model uncertainties stem from the calculation of *f* values and general input data. The movement of water between the upper soil layers and groundwater is not well understood (Jewitt, 2006; Wilcox, 2010). Wu et al. (2015) found that even shallow rooted plants like grasslands are capable of using ground water by exploiting the capillary rise fluxes. Therefore, these factors may introduce minor errors in the subsequent f values calculated. However, results from this study and elsewhere (Morillas et al., 2013; Zhang et al., 2010, 2016) suggest that the approach is robust in reproducing dynamics in ET. Other uncertainties are linked to the MODIS LAI (Myneni et al., 2002) used. For example, McColl et al. (2011) found that MODIS over estimated LAI over patchy vegetation (< 0.6) and underestimated LAI in densely vegetated areas. Serbin et al. (2013) also reported moderate inconsistency between measured and MODIS LAI in Manitoba. Therefore, there is a distinct possibility that these patterns could also be playing out at the present study sites as LAI was relatively low. Hence, estimation biases observed in this work could also be linked to uncertainties in MODIS LAI. 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. At the Truro farm, the land was previously invaded by woody invasive alien species (IAPs) and hence a plot of LAI trajectories since MOD15A became available helped the study in differentiating IAP signal from that of the grassland. Hence, the modelled fluxes are a true reflection of dynamics of ET over the landscape. The use of maximum LAI values for the same vegetation type found in other areas could also be useful.

### 7.6 Conclusion

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 soil evaporation 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 complex stomatal behaviour and the  $E_s$  had a huge influence on estimated ET particularly at the EGR. The empiral algorithms developed in this study need further refinement once a larger database has been accumulated.

# 7.7 References

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# CHAPTER 8: EXPLORING DYNAMICS OF EVAPOTRANSPIRATION TRENDS IN SELECTED LAND COVER CLASSES IN A SUB-HUMID REGION OF SOUTH AFRICA

Part of this chapter has been published in a peer-reviewed conference proceedings:

Gwate, O., Mantel, S. K., & Palmer, A. R. (2016). Exploring dynamics of evapotranspiration in a semi-arid grassland of South Africa. In *Proc. of the 10th International Rangeland Congress, Saskatoon, Canada, 16 - 22 July 2016.* (pp. 1095–1097).

OG collected, analysed the data and wrote the text in this chapter.

### 8.1 Abstract

Land cover change is a pervasive force affecting grasslands and it influences the relationship between precipitation (P) and evapotranspiration (ET). The present study sought to determine variations in catchment scale ET attributable to land cover change over a grassland in the Eastern Cape, South Africa. Pursuant to this, remotely sensed rainfall and ET data were used to compute the evaporative index  $\left(\frac{ET}{P}\right)$ . Available land cover maps for the study area were evaluated to establish land cover change trajectories. Subsequently, these maps were used to extract annual ET from the MOD 16 ET product. Before using these maps, a statistical method of detecting breaks in time series data was applied in order to diagnose a shift in ET with land cover change to enable the application of an appropriate map for retrieving ET. Rainfall and ET data were subjected to trends and shifts detection tests to determine the existence of abrupt change and trends in the data. Total catchment rainfall and ET displayed a decreasing pattern. Grassland and built-up ET showed a step change (p < 0.05) from a low to a high, suggesting sudden changes in these land cover types. The forest cover revealed a marginal positive trend (p < 0.1), indicating that forest cover change was a slow process in the study area. The evaporative index suggests that land cover influenced ET and this was confirmed by changes in the catchment parameter (w). During years of low rainfall, the evaporative index was higher than years of high rainfall and this was due to atmospheric demand. For some years, the evaporative index was >1 even for shallow rooted vegetation, indicating the role of runoff and the strong coupling between sub surface water and the upper soil in driving ET in the study area. Although changes in ET were largely attributable to land cover changes, drought related to global forces seems to have also influenced ET since increasing aridity tends to be accompanied by higher evaporative index.

*Keywords*: rangelands, land cover change, evapotranspiration, remote sensing, evaporative index, dryness index, MOD16 ET product, TAMSAT dataset

### 8.2. Introduction

Evapotranspiration provides an essential link between the water, carbon and energy cycles and hence, changes in ET will have feedbacks on various aspects of life on earth. Therefore, understanding the temporal and spatial dynamics in ET in a context of global environmental changes linked to climate and land cover changes is crucial. The influence of land cover change on hydrological fluxes has been the subject of long term debate (Zhou et al., 2015). In South Africa, invasive alien plants (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 (Boisier et al., 2013; Houspanossian et al., 2017). In South African grasslands, there has been marked increase in woody plants such as Acacia mearnsii (O'Connor et al., 2014; Stevens et al., 2016) and may undermine the ability of these grasslands to support local livelihoods. The importance of grasslands in supporting world agriculture and other ecosystem services is well documented (FAO, 2015). Therefore, it becomes important to determine the response of grassland eco-hydrological processes such as ET to land cover changes. Globally, research on the link between hydrological fluxes and land cover change has yielded different results. For example, it has been shown that changes related to water yield vary from one catchment to another, although in large catchments (> 1000 km<sup>2</sup>) land cover change had limited effects, no effects or even positive effects on water yield (Zhou et al., 2015). Therefore, it is crucial to investigate the influence of land cover change in sub-humid grasslands of South Africa to determine the nature of their response and to establish whether there is any convergence with global trends.

One of the pervasive effects of land cover change is its influence on the partitioning of precipitation into its various components such as ET and runoff. ET is the biggest flux of the hydrological cycle after precipitation and it is critical in determining water availability at a place (Mao et al., 2015). Global change studies project future water scarcity in many parts of the world. Therefore, it becomes imperative to understand ET for each land cover type in a given system as change in land use in water-limited systems is leading to conflicts around water allocation and licensing (Vettorazzi & Valente, 2016). In South Africa, forestry, livestock grazing, cultivation, as well as rural and urban settlement arguably represents such a conflicting space. Therefore, quantifying water use in each land cover type can provide valuable information to water regulators in their attempts to resolve these conflicts. Hence, it becomes important to determine the ET 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 mean actual evaporation as a function of the aridity index. This framework relates the evaporative index  $\left(\frac{ET}{P}\right)$  to the dryness index  $\left(\frac{PET}{P}\right)$ , where *P* denotes mean annual precipitation (rainfall) and PET is potential ET. The framework assumes that the mean annual

evapotranspiration over a large area is controlled by water availability and vapour pressure deficit. Water availability is approximately equivalent to precipitation, while net radiation can be used as a proxy for atmospheric demand. On the basis of this, under very dry conditions, actual ET will approach precipitation, and under very wet conditions, evapotranspiration will asymptotically approach the atmospheric demand (Wang et al., 2016) and this can be expressed as:

$$\frac{ET}{P} \to 1$$
, when  $\frac{R_n}{P} \to \infty$  (very dry conditions) [8.1]

$$ET \to R_n$$
, when  $\frac{R_n}{P} \to 0$  (very wet conditions) [8.2]

where  $R_n$  is net radiation, an equivalent of potential ET (PET).

The original Budyko framework did not consider vegetation cover and other catchment characteristics since the long-term ET 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 ET by incorporating catchment characteristics such as land cover and soil moisture (Zhang et al. 2001; Zhang et al. 2004; Zhang et al. 2010; Gentine et al. 2012; Chen et al., 2015). These approaches allow catchment parameters 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; Zhang et al., 2010; Chen et al., 2015) in order to parameterize a catchment parameter that incorporates catchment properties connected to land cover. The model is expressed as:

$$\frac{ET}{P} = 1 + \frac{PET}{P} - \left[1 + \left(\frac{PET}{P}\right)^{w}\right]^{1/w}$$
[8.3]

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.

It should be noted that, given the same dryness index, catchment hydrology will still vary owing to these specific catchment characteristics. Vegetation cover serves as a very good integrated indicator of these eco-hydrological impacts on water and energy fluxes since the influence of all these other factors can be seen in vegetation characteristics (Li et al., 2013). 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 & Farquhar, 2011). Hence, *w* is essentially indicative of vegetation characteristics. Results

from studies adopting equation 8.3 have helped to evaluate the impacts of land cover change on catchment hydrological fluxes (Zhang, et al., 2004; Chen et al., 2015; Zhou et al., 2015).

The evaporative index  $\left(\frac{ET}{P}\right)$  can also be a useful stable measure to discern the influence of land cover dynamics on ET. This study links land cover change to shifts in the  $\frac{AET}{P}$  ratio. It should be noted that ET and  $\frac{ET}{P}$  ratio are in part a function of the dominant land cover. With the availability of ET data such as the MOD16 ET product (Mu et al., 2011), it is now possible to explore actual  $\frac{ET}{P}$  ratio on finer temporal and spatial scales. Determining landscape ET and  $\frac{ET}{P}$ ratio is difficult since measurements of P and ET are fraught with many errors. In addition, precipitation data is frequently obtained from isolated rainfall gauging stations while actual ET is obtained from flux towers, surface layer scintillometers and open-top-chambers. These approaches essentially provide point samples and may not be useful in heterogeneous landscapes and where there are patchy or even absent measurement stations. In heterogeneous areas, point estimates are inadequate, and at best can be used to parameterize and validate spatially explicit models. Water use of different land cover types in a catchment may not be easily quantified particularly in ungauged catchments. Consequently, remote sensing technology has become vital in providing ET values on a continuous basis at high temporal and spatial resolutions in such environments (Tarnavsky et al., 2014; Liou & Kar, 2014). Global datasets such as the MOD16 ET product (Mu et al., 2007, 2011) provide an opportunity to evaluate spatial and temporal variation in water use. At the same time remotely sensed precipitation datasets such as Tropical Applications of Meteorology Using Satellite Data and Ground-Based Observations (TAMSAT, Maidment et al., 2014; Tarnavsky et al., 2014) provide P data at a fine temporal and spatial resolution for the African continent, and is useful for these largely data scarce areas.

Remote sensing technology is a valuable tool for evaluating spatial distribution of phenomena. Through the application of remote sensing techniques, land cover change mapping has become easier. Notwithstanding rapid changes such as clear felling of vegetation, land cover change is essentially a slow process. Land cover change is a global phenomenon mainly driven by agriculture and settlement expansion (Lambin et al., 2003; Eva et al., 2006; Loveland & Acevedo, 2006). 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 ET to land cover change it is important to detect the onset of

change in ET in response to the generally slow process of land cover change. However, this is often a difficult task, but a very important one in order to correctly attribute fluxes to land cover change. Therefore, robust statistical methods of searching for breaks in longitudinal data become critical. The aim of the study was to assess the response of ET to land cover changes on a grassland system in South Africa. Therefore, remotely sensed datasets in the form of TAMSAT and MOD16 ET product were deemed suitable for the study.

# 8.3. Material and Methods

### 8.3.1 Study area

Quaternary catchment S50E in South Africa was selected for the study and the Tsomo river which drains the catchment is perennial (Fig. 8.1). Catchment S50E terminates at the  $150 \times 10^6$  m<sup>3</sup> capacity Ncora dam and it covers 447.60 km<sup>2</sup>. The area lies on the southern Drankensberg grassland (Mucina et al., 2006) with altitude ranging from 1010 to 1700 m. The area is a natural grassland ecosystem under communal tenure where maize mixed farming is practised (Garrity et al., 2012). The grassland is under pressure from land cover changes. Long term modelled mean annual rainfall for the area is 772 mm yr<sup>-1</sup> and average pan evaporation is 1742 mm yr<sup>-1</sup> (Schulze, 1997). Quaternary catchment S50E is ungauged and hence presents challenges to modelling hydrological fluxes.





# 8.3.2 Methods

# Land cover data

Available land cover maps for the study area were evaluated to determine trajectories in land cover change. An extract of the 2000 National Land Cover (NLC) map (Fairbanks et al., 2000) for the study site and the 2014 map (Okoye, 2016) were used. These maps had a spatial resolution of 30 m. The 2000 NLC was the first standardised land cover dataset for South Africa, Lesotho and Swaziland and it provides the baseline data. On the other hand, the 2014 map was prepared by Okoye (2016) specifically for the study area and it adapted the 2000 land classes by combining some land cover classes. Subsequently, the new land cover classes for the study site were defined (Table 8.1).

NLC 2000 class	Adapted 2014 class
Degraded Unimproved (natural) Grassland	Grassland
Unimproved (natural) Grassland	
Shrubland and Low Fynbos	
Forest (indigenous)	
Thicket, Bushland, Bush Clumps, High Fynbos	Forest
Bare Rock and Soil (natural)	Bare Rock / Soil
Mines and Quarries (surface-based mining)	
Cultivated, permanent, commercial, irrigated	Cultivation
Cultivated, temporary, commercial, dryland	
Cultivated, temporary, subsistence, dryland	
Forest Plantations (clear felled)	Plantations
Forest Plantations (Other / mixed spp.)	
Forest Plantations (Pine spp.)	
Urban / Built-up (residential, formal township)	Built-up
Waterbodies	Waterbodies
Wetlands	Wetlands

Table 8.1. Adaptation of the 2000 NLC to the 2014 map of the study site (Okoye, 2016).

# **MODIS** data

Moderate Resolution Imaging Spectroradiometer (MODIS) evapotranspiration dataset (MOD16 ET, Mu et al., 2007; 2011) provides dynamic global ET data over vegetated surfaces. The MOD16A3 ET product was acquired from the Numerical Terradynamic Simulation Group at the University of Montana (http://www.ntsg.umt.edu/project/mod16#data-productprod) to evaluate the ET dynamics for the study area. The MOD16A3 ET is an annual product with a spatial resolution of 1 km. Mean annual ET or actual ET (AET) and potential ET (PET) were extracted for application in the study.

### **Rainfall data**

The TAMSAT dataset (Maidment et al., 2014; Tarnavsky et al., 2014) was applied to derive rainfall pattern for the study site. The dataset initially covered West Africa but has been extended to cover the whole of Africa from 1983 to date (Tarnavsky et al., 2014). The TAMSAT method combines geostationary Meteosat data with gauge observations through a calibration approach that exploits both data sources. The gauge information is only used to

generate climatological calibrations that vary spatially and monthly to reflect the geographical and temporal variations in the average rainfall climate across Africa. These empirically derived calibration parameters of the TAMSAT system do not change from year to year, removing the need for simultaneous gauge data (Tarnavsky et al., 2014). The temporal variation in rainfall, derived from the TAMSAT African Rainfall Climatology and Time Series (TARCAT) dataset, is therefore largely unaffected by gauge sampling biases. Based on the premise that cold clouds produce most of rainfall across Africa, rainfall estimates are determined by applying the predetermined calibration parameters to cold cloud duration (CCD) fields calculated from thermal infrared (TIR) data (Maidment et al., 2014; Tarnavsky et al., 2014). Data for the study site the TAMSAT website (http://www.tamsat.org.uk/cgiwas obtained from bin/data/index.cgi). This data set was suitable for the study as it provides mean rainfall estimates at spatial resolution of 4 km. The data is available on daily, decadal, monthly and seasonal time periods.

### Comparison of TAMSAT and automatic weather station (AWS) data

The TAMSAT data set coinciding with the pixel of the AWS at Somerton farm in the Eastern Cape, South Africa were compared. The non-parametric Mann-Whitney test was applied on the two datasets to establish whether the medians of two datasets were similar. Subsequently, the TAMSAT data set was applied to quaternary catchment S50E to derive mean catchment rainfall estimates.

### **Determining evaporative index**

Available land cover maps (2000 and 2014, 30 m resolution) were evaluated in ArcGIS version® 10.2 and resampled to 1 km resolution to match the MOD16A3 ET product. Using the zonal spatial analyst tool, the mean annual AET from the MOD16A3 ET product for the study site was extracted for the period 2000 to 2014. In order to link ET to land cover change the evaporative index  $\left(\frac{ET}{p}\right)$  for each year had to be prepared. However, the challenge was on selecting the appropriate map to use for respective years. Often, land cover change is a slow process unless there is sudden intervention like settlement or tree cutting. The study applied the method of cumulative residuals (Allen et al., 1998; Costa & Soares, 2009) to detect breaks in the AET pattern between 2000 and 2014. On the basis the results, different maps were applied to the respective years to extract ET data. Then using the TAMSAT rainfall data and MOD16 ET,  $\frac{ET}{p}$  ratios for different land cover classes for the years 2000 – 2014 were computed.

### Change detection in ET data

In order to understand trajectories in AET at a quaternary catchment scale, annual totals (2000 -2014) were subjected to trends analysis using the Mann-Kendall trend test. This is a nonparametric test which measures the tendency of a trend to be increasing or decreasing. The test statistics range from +1 to -1 with a zero value indicating no consistent trend (Kendall, 1975; Mann, 1945) and the trend was tested at the 95% confidence level. However, time series data tend to suffer from autocorrelation and this increases the probability of the Mann-Kendall test to detect a significant trend when in fact the trend is absent (Yue et al., 2002). Hence, prior to trend testing, the data was subjected to three white noise tests (Box-Pierce, Ljung-Box and McLeod-Li tests) at the 0.05 alpha level in order to determine any serial correlation in the data and pre-whitening implemented when necessary. A white noise process is a continuous time series of random and uncorrelated values (Mahan et al., 2015). When the data set fails white noise tests, the data is transformed through Box-Cox transformation (Sakia, 2012). In order to remove the trend and the seasonal component, the differencing method was applied on the Box-Cox transformed series to 'whiten' it (Yue et al., 2002). After pre-whitening the Mann-Kendall test was then applied on the data. Subsequently, the Sen's slope estimator was used to determine the magnitude of the change (Sen, 1968). The Sen's slope estimator is a nonparametric method used to estimate the rate of change per unit time and is robust since it is insensitive to the presence of outliers (Patarl & Kahya, 2006; Traore et al., 2014). The Pettitt or median change point test (Pettitt, 1979) was also applied on the annual AET data in order to detect the presence of abrupt changes in the dataset. This is a non-parametric test which is relatively insensitive to changes in distributional form (Kundzewicz & Robson, 2004). These trend and step change detection methods have been applied extensively in the analysis of time series data (Traore et al., 2014; Gebremicael et al., 2016; Onyutha et al., 2016). The statistical tests were performed using R-3.1.3 and XLSTAT 2017.1 software packages

# Detecting changes in the rainfall data

The TAMSAT rainfall data coinciding with quaternary catchment S50E was also subjected to step change and trend detection tests in order to discern the pattern over the study period (2000 – 2014). Consequently, Mann-Kendall trend, Sen's slope estimator and Pettitt tests were applied to better understand the rainfall trajectories. Prior to the application of the Mann-Kendall test, the data was subjected to white noise tests and if necessary pre-whitening was implemented. To gain further insight into the pattern of the regional rainfall in the study area,

observed data from a weather station at Mount Alyff area was also investigated. The Mount Alyff site falls under the same rainfall belt with the present study (Schulze, 1997). Similarly, the Mann-Kendall trend test, Sen's slope estimator and the Pettitt test) were applied on the available Mount Alyff dataset spanning from 1923 to 1985. Further, the Mount Alyff dataset was combined with the TASMAT dataset (1986 – 2014) to provide a long-term continuous dataset to discern regional rainfall pattern. Then, the above approaches for detecting change were applied.

# **Estimating the catchment parameter**

In order to detect the influence of catchment characteristics such as land cover change on ET, the catchment parameter (w) was estimated using optimization by fitting equation 8.3 to observed actual ET (AET) from the MO16A3 product in the R-3.1.3 software environment by exploiting the *rgenoud* package (Mebane & Sekhon, 2011). The optimization sought to minimise the difference between the observed and the predicted AET for each year. It should be noted that the catchment parameter is a proxy for integrated catchment characteristics largely linked to land cover (Chen et al., 2015). Subsequently, the catchment parameter was tested for step change (Pettitt test) and existence of a trend (Mann-Kendall test) and the magnitude of change was estimated using the Sen's slope over the years (2000 – 02014).

### 8.4. Results

### **8.4.1 Detecting change**

The cumulative residuals showed a falling pattern up to the year 2003 and then a rise henceforth (Fig. 8.2). Therefore, the year 2004 seems to be an inflection point in annual catchment ET, although both the Mann-Kendall and Pettitt test could not detect significant changes (p > 0.05) in the ET pattern. Hence the 2000 map was used to extract ET up to the year 2003 while the 2014 map was used for the rest of the period.



Figure 8.2. Detecting breakpoint in MOD16A3 ET time series data (2000 – 2014).

# 8.4.2 Trends in annual total catchment ET, PET and rainfall

In order to determine the appropriateness of the TAMSAT dataset in the study area, the former was compared with the data from an AWS at Somerton farm in the Eastern Cape. The Mann-Whitney test showed that the medians of the two datasets were similar (Mann-Whitney U = 3002, z = -1.08,  $N_1 = N_2 = 85$ , p > 0.05 two tailed) and subsequently, the dataset was applied with a high degree of confidence. During the study period (2000 - 2014), mean  $\pm$  standard deviation of annual rainfall, AET and PET in the period were  $444.8 \pm 62$ ,  $528.9 \pm 75$  and  $1873 \pm 59$  mm respectively. Maximum annual rainfall was recorded in 2002 while maximum AET was observed in 2006. Maximum rainfall received coincided with an AET of 418 mm (Fig. 8.3). The lowest rainfall (409 mm) was observed in 2013 and the lowest AET was recorded in 2003 (349 mm) (Fig. 8.3). Generally, years of higher rainfall coincided with reduced AET compared to rainfall while those of low rainfall were accompanied by high AET relative to rainfall received (Fig. 8.3). The PET was consistently higher than AET throughout the period (Fig. 8.3).



Figure 8.3. Mean annual (MOD16A3) potential evapotranspiration (PET), Actual evapotranspiration (AET) and rainfall (TAMSAT) in the study area (2000 – 2014).

With respect to rainfall and AET, no significant step changes or trends were detected during the study period (2000 - 2014). However, the Sen's slope estimator showed that mean annual rainfall has been falling at a rate of 7 mm yr<sup>-1</sup> within -9 and -4.84 confidence interval. Mean annual AET was falling at a rate of 2.4 mm yr<sup>-1</sup> within -3.13 and -1.51 confidence interval (Fig. 8.4a-b). To get an insight into the regional rainfall pattern, long term observed data from Mount Ayliff (1923 – 1985) which is 100 km away in the same rainfall zone (Schulze, 1997) also indicate an annual decrease in rainfall of 1.8 mm yr<sup>-1</sup> within -2.53 and -1.03 confidence interval (Fig 8.4c). When the Mount Ayliff dataset 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 (Fig 8.4d).



Figure 8.4. Annual pattern in a) rainfall and b) AET in the study area c) rainfall changes from Mount Ayliff weather station (1923 – 1985) and d) combined Mount Ayliff weather station (1923 – 1985) and TAMSAT (1986 – 2014) rainfall datasets. Dotted lines indicate average rainfall.

During the study period (2000 - 2014), the Pettitt test detected abrupt change (p < 0.05) in ET for grassland and the built-up land cover types (Fig. 8.5a-b). The onset of change in ET for the two land cover types happened from 2005 and both showed an increasing change point (Fig. 8.5a-b). The pattern of ET for forest, plantation and cultivation is presented (Fig. 8.5c-e). The Mann-Kendall test detected a marginally significant trend (p < 0.1) in forest ET 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 ET while cultivation (-0.03) and plantation (-3.54) indicated the propensity of a declining trend in the ET during the study period.



Figure 8.5. Homogeneity tests of time series ET: a) grassland (Pettitt test < 0.05), b) built up (Pettitt test p < 0.05), c) Forest (Mann-Kendall test < 0.1) and d-e) plantation and cultivation (Mann-Kendall test p > 0.05). Dotted lines indicate the mean ET over particular periods.

In order to have a better understanding of the these changes in ET, the Sen's slope was computed to show the magnitude of annual dynamics in ET during the study period (2000 - 2014). With respect to individual land cover types, grassland had the highest rate of annual increase in AET followed by built-up and forest cover types during the study period (2000 - 2014). On the other hand, cultivation and plantation cover types experienced an annual decrease in AET (Fig 8.6).



Figure 8.6. Annual rate of change in AET for different land cover types in the study area (2000 -2014).

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, Fig. 8.7). The Kendall's tau was -0.43 and the Sen's slope showed an annual decrease in *w* of 0.03 within -0.03 and -0.024 confidence interval.



Figure 8.7. Trends in the catchment parameter (w) between the years 2000 - 2014
#### 8.4.3 Land cover change and evaporative index

From a rangeland management perspective, the study selected the important land cover types 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  $\frac{ET}{p}$  ratio (Table 8.2). The decline in the plantation cover type was accompanied by 18% decline in the evaporative index. However, the reduction in grassland cover was accompanied by an increase in the  $\frac{ET}{p}$  ratio (Table 8.2). The evaporative index for other selected land cover types increased remarkably with  $\frac{ET}{p}$  ratios being higher (4.9 – 31%) in 2014 compared to the year 2000 (Table 8.2).

 Table 8.2. Land cover change and evaporative index in the study area.

*Land cover	2000		2014	2014	
	Percentage	$\overline{ET}$	Percentage	ET	
	cover	Р	cover	Р	
Grassland	75.7	0.72	56.63	0.94	
Plantation	3.94	1.15	1.80	0.94	
Forest	5.43	0.94	10.76	1.02	
Cultivation	4.98	0.82	18.10	0.86	
Built-up	5.78	0.75	9.46	0.90	

\*Land cover data was obtained from Fairbanks et al. (2000) and Okoye (2016).

# 8.4.4 Impact of woody encroachment on grassland evaporative index $\left(\frac{ET}{P}\right)$ ratio

The study further selected grassland, plantation and forest cover types in order to understand the likely hydrological consequences of woody encroachment in the study area. The relationship between the evaporative index and rainfall for the selected land cover types were significant (p < 0.001). 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, Fig. 8.8). 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 (Fig. 8.8).



Figure 8.8. The relationship between annual precipitation and the evaporative index in the quaternary catchment S50E for three land cover classes (2000 - 2014): top dotted line – plantation (y = -0.002x + 2.3, R<sup>2</sup> = 0.59, p < 0.001), middle – forest (y = -0.0021x + 2.1, p < 0.001, R<sup>2</sup> = 0.65) and bottom – grassland (y = -0.0021x + 2.02, R<sup>2</sup> = 0.58 p < 0.001).

#### 8.5 Discussion

#### 8.5.1 Data quality

Admittedly, there are uncertainties related to the MOD16 ET product connected to input meteorological data and upstream input data of leaf area index and land cover (Zhao et al., 2005). Despite these challenges, the MOD 16 ET product has been validated globally (Mu et al. 2011; Kim et al. 2012; Ruhoff et al., 2013; Ramoelo et al., 2014) and results indicate that the model provides reasonable estimates of ET. Therefore, the fluxes derived for this study are likely to be accurate. The biggest challenge was the selection of the land cover map to extract ET values for respective years since land cover change is often a slow process. However, the application of the cumulative residual method (Allen et al., 1998; Costa & Soares, 2009) to search for breaks in the ET data was useful. It was against this background that the study is confident that the extracted ET values are reflective of the land-atmosphere transfer in the study area. The point of break in 2004 is reasonable since the images that produced the 2000 map were acquired earlier than 2000.

#### 8.5.2 Patterns in ET and rainfall

Decreasing trajectories in rainfall and AET, albeit, not statistically significant were found. However, with respect to AET the method of cumulative residuals detected a shift in the dataset between 2003 and 2004. Willmott (1981) reported that the concept of statistical significance should be viewed with caution since lack of statistically significant differences does not imply absence of substantial dissimilarities or trends. Therefore, the observed Sen's slope for AET and rainfall are important indicators of the magnitude and direction of change of the annual data. This helps to better understand hydrological fluxes and management implications for the study area. The rainfall derived from satellites and observed rainfall from the weather station was similar and this entrenches the importance of satellite derived precipitation datasets in areas without ground based observation stations. MacKellar et al. (2014) reported a statistical significant reduction in the number of rainy days in one weather station along the northern coast of the Eastern Cape and this was close to the study site. Engelbrecht et al. (2009) also projected decline in rainfall over the study area in light of climate change scenarios. A longterm (1923-1985) rainfall data series was analyzed for the town of Mount Ayliff, situated ~100 km away from the study site in a very similar rainfall zone (Schulze, 1997). Both the observed Mount Ayliff data series and when it was extended (1985-present)with TAMSAT dataset showed a declining pattern, albeit statistically insignificant. These results are consistent with the decreasing trajectory revealed by the TAMSAT dataset at the present study site. The potential decline in ET is consistent with long term global ET trends trajectories. Globally it has been observed that there was widespread decline in wind speed leading to a decline in evaporative demand as shown by declining trends in pan evaporation in many places across the terrestrial globe (Roderick et al., 2007; McVicar et al., 2012). In South Africa, Eamus & Palmer (2007) reported declining pan evaporation at two stations (Eastern and Northern Cape provinces) while Hoffman et al. (2011) also observed declining trend in the pan evaporation (Western Cape province).

#### 8.5.3 Dynamics in the evaporative index

The results suggest that both land cover and rainfall changes influenced ET in the study area. The problem of woody thickening in rangelands has been reported widely in southern Africa and has traditionally been attributed to land use change such as exclusion of fire and overgrazing (O'Connor et al. 2014). However, recently, there is emerging evidence that global drivers coupled with increase in atmospheric  $CO_2$  and nitrogen fertilization tend to favour woody species in grasslands (Stevens et al., 2016). In the present study area, the densification of the invasive *A. mearnsii* has been reported (Gwate et al., 2016) and this may explain the presence on a trend observed in the ET of the forest cover type. With respect to plantation cover, the decrease in land cover was accompanied by a decline in evaporative index and this could be due to clear felling of plantation and replacing it with a new crop (Mahlungulu village community members, pers comm., 2015). The plantation was for *Pinus* spp. and hence age

dynamics are critical in water use. This is consistent with the view that the size and age of *Pinus* plants influenced ET with older plants having lower water use efficiency as compared to young plants (Skubel et al., 2015; Swaffer & Holland, 2015). The increase in cultivated land also had corresponding effect on ET since such crops tend to have higher leaf area index 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 is converted into green water. Results also suggest that built-up areas are crucial in partitioning hydrological fluxes and confirm that they are not a desert but contribute significantly to ET particularly after rainfall events (Ramamurthy & Bou-Zeid, 2014). In addition, the step-change in ET observed in the build-up area is indicative of rapid settlement in the catchment.

The evaporative index for the grassland cover increased with a significant decrease in the area covered between the years 2000 and 2014. This result is consistent with the observed ET trends on grassland ecosystems at a global scale (Gang et al., 2016). The first ten years of the  $21^{st}$  century were recognised as the warmest since application of instruments in weather observation (Zhao & Running, 2010). Despite drought prevalence in the grasslands of the world during this period, pure grasslands displayed an increasing trend in ET and declining water use efficiency (Gang et al., 2015; Gang et al., 2016). Therefore, the observed ET changes in the study area were consistent with the global patterns. The exclusion of fire in the grassland could also be causing the leaf area index to be relatively high during the growing season and this has a consequence of increasing ET. The monthly MODIS burnt areas MCD45A1 product (Boschetti et al., 2008) also indicates a reduction in fire frequency from an average of three months per season (2000 – 2005) to one fire incident per season (2006 to 2014) in the catchment. Therefore, land cover change may not fully explain dynamics in grassland ET but a combination of factors such as land management linked to fire exclusion and also global forces related to warming. These factors could have possibly led to a step-change in grassland ET.

#### 8.5.4 Dynamics in the catchment parameter (w)

An investigation of the catchment parameter suggests that dramatic land cover changes have occurred in the period under study. The catchment parameter represents the integrated effects of catchment characteristics such as vegetation cover, soil properties, catchment slope and soil storage capacity on water balance (Zhang et al., 2004; Chen et al., 2015). Results reveal that the catchment parameter 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 8.3 in this thesis 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). 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 & Farquhar, 2011; Li et al., 2013) and hence, w is essentially indicative of vegetation characteristics. It is against this background that the observed changes in the catchment parameter could largely be indicative of dynamics in watershed properties related to land cover. The breakpoint in ET dataset between 2003 and 2004 also suggests that the influence of other factors other than climate were also crucial and in the short term these are captured within the vegetation characteristics (Roderick & 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 reduced (Zhou et al., 2015). This could be due to the observed densification of woody plants (Gwate et al., 2016) that have higher ET 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  $1 \le w \le 2$  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  $1 \le w \le 2$  (Zhou et al., 2015). On the other hand, in areas with w > 2, the hydrological response of catchments was more coupled to P/PET. Average catchment parameter from this study  $(1 \le w \le 2)$  suggests that hydrological response was strongly coupled to land cover changes. 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 ET showed a decreasing trajectory, some land types recorded mean annual increase in ET. Ideally, one would expect corresponding decrease in ET across the land cover types since precipitation is the main driver of ET. Admittedly, extra water to drive ET could have come from runoff, ground water as well as capillary action for specific land cover types, indicating the influence of non-steady state characteristics at the catchment. Hence, the increasing pattern in ET in some land cover types suggests a response to non-steady state catchment characteristics whose signal can be traced in

vegetation cover. As such land cover change could have been the main driver of dynamics in ET for the study area. This suggests that land cover change can have serious hydrologic consequences in the grassland. Therefore, high evaporative flux by woody species will reduce water availability to support grasslands. Within the broader context of climate change, many grassland sites are likely to experience more warming and droughts, resulting in decreasing grass biomass (Gang et al., 2016) and this will adversely affect the livestock and wildlife ranching farming systems. For the region within the study area MacKellar et al. (2014) reported reduction in the number of rainy days in the region and this is likely to further undermine water available to support rangeland grass production. Although increase in cultivated land was accompanied by a corresponding increase in the evaporative index, the decreasing ET 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. Yimam et al. (2015) also reported higher water use efficiency of sorghum compared to switch grass. It should be noted that in the study area, maize and sorghum are the main cultivated crops.

#### 8.5.5 Influence of woody encroachment on ET

A plot of the evaporative index against mean annual rainfall illuminated the possible hydrologic impacts of woody encroachment into grasslands of the Eastern Cape. The ET occasionally exceeded rainfall and this may have been caused by additional moisture from runoff along the rivers since a perennial river drains the quaternary catchment and A. mearnsii is particularly dense in riparian zones. In addition, there is a possibility that the woody vegetation could have been accessing ground water. For example, Canadell et al. (1996) reported that Pinus spp. root depths ranged from 2 – 7.5 m while Le Maitre et al. (2015) noted that A. mearnsii rooting depth was > 4 m. Above all, it has been observed that the movement of ground water and its link to the upper layers of the soil is one of the least understood aspect of the hydrological cycle (Jewitt, 2006; Wilcox, 2010). In addition, Wu et al. (2015) have demonstrated that even grasslands are capable of using ground water by exploiting the capillary rise fluxes. Therefore, the long roots, runoff and capillary action could explain the >1 evaporative index reported even for the grassland cover in this thesis. It should be noted that most A. mearnsii infestation is also concentrated in riparian zones, providing them with excess water from runoff. Above all, the observed evaporative index for different vegetation were consistent with the basic premise of the Budyko framework that in water limited ecosystems, ET approaches and exceeds precipitation if there is additional water supply.

PET was consistently higher than AET and rainfall throughout the study period and this suggests that there was high atmospheric demand and more energy was available to drive ET. Hence, the study area was water limited in terms of ET. 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 vapour pressure deficits associated with dry conditions resulting in a higher evaporative flux. During years of high precipitation, atmospheric demand was relatively low and as such low ET was experienced. Results were consistent with the theoretical framework of Zhang et al. (2001; 2004) that systems dominated by woody vegetation tend to have higher ET compared to those dominated by grasses. Therefore, land cover changes related to the encroachment of woody vegetation in the study area is altering ET patterns.

#### 8.6 Conclusion

The study sought to determine dynamics in ET attributable to land cover change. The evaporative index proved to be useful in tracing the effects of land cover change on ET. Therefore, the observed dynamics in ET could largely be linked to land cover changes as shown by dynamics in the catchment parameter and land cover maps. However, dramatic land cover change in some cases does not result in a corresponding change in ET as observed in the grassland cover type. In such cases, global processes related to warming/ increasing droughts also seem to modulate evaporation. There could be a strong connection between sub surface and surface water in driving ET in the study area since the evaporative index was >1 in some cases. This can also be explained by runoff which could have provided excess water. The study has also determined a catchment parameter (w) which may be useful for future hydrological studies in this ungauged catchment. Land cover change influences ET and this may have serious hydrologic consequences in rangelands. Understanding ET in grassland should be informed by an understanding of local and global processes that modulate water use in the landscape.

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# CHAPTER 9: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

#### 9.1 Introduction

Global and local forces are influencing rangeland ecosystem functioning. In South Africa, woody thickening and dynamics in water and energy fluxes are some of the positive feedbacks from these global and local forces. The problem of woody encroachment has been recognised in South Africa (Wigley et al., 2010; Buitenwerf et al., 2012; O'Connor et al., 2014; Stevens et al., 2016). In the Eastern Cape, woody encroachment is taking place on the dominant Grassland Biome (Mucina et al., 2006) and this has implications on its ability to provide forage resources to people dependent on livestock and wild life ranching. At the same time within the broader context of climate change, good management of available water is essential in pursuit of integrated water resources management (IWRM) and also to enhance global food production systems (Molden et al., 2010) in a context of water scarcity. ET or its energy equivalent, latent heat flux (LE), forms the biggest flux of the hydrological cycle after precipitation yet it is not well understood (Liou & Kar, 2014; Amatya et al., 2016). It is against this backdrop that the need to explore ways of managing rangelands in order to optimise herbage production cannot be overemphasised, particularly with respect to the Eastern Cape. In addition, within the purview of climate change, an understanding of water and energy fluxes in rangelands is critical to improve knowledge on ecological processes so as to better deal with the consequences of climate change such as water scarcity. To address these overarching themes in global change, this thesis used the Grassland and the Albany Thicket (AT) Biomes to understand dynamics in grass biomass production, energy and water fluxes in the Eastern Cape. Drawing from Chapter 1, a number of outstanding issues and challenges in the management of invaded rangelands, measuring and modelling water vapour fluxes were identified. The aim of the study was to contribute towards effective management of rangelands by understanding the dynamics in rangeland production and water use. Accordingly, the key research objectives of this thesis were defined as:

1. To determine the impact of *A. mearnsii* invasion on rangelands grass production and to explore optimal ways of managing rangelands invaded by IAPs such as *A. mearnsii*.

2. To understand the dynamics in water vapour and energy fluxes on un-invaded examples of grassland and AT biomes, and to explore biophysical factors influencing the partitioning of these fluxes in the latter.

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3. To test the ability of the Penman-Monteith-Leuning (PML) ET model to reproduce observed ET over the AT biome which is strongly believed to be controlling water use through stomatal behaviour.

4. To validate the PML and the Penman-Monteith-Palmer (PMP) models in the Grassland Biome using a large aperture scintillometer (LAS).

5. To develop simplified algorithms for estimating actual ET in semi-arid data scarce landscapes of the Eastern Cape.

6. To evaluate the link between land cover change and ET at a quaternary catchment scale.

The result of the study described in this thesis is a body of work that demonstrates the impact of A. mearnsii on rangelands and an exploration of optimum ways of managing rangelands invaded by IAPs such as A. mearnsii. These two objectives were a response to the ongoing clearing of invasive alien plants (IAPs) under the auspices of the Working for Water (WfW) programme (van Wilgen et al., 2008; Le Maitre et al., 2011; van Wilgen et al., 2011; McConnachie et al., 2012; van Wilgen & Richardson, 2014) and the need for an assessment of the post-clearing productivity of restored grasslands. Secondly, the thesis explored water vapour and energy fluxes over the Grassland and Albany Thicket Biomes. Here the focus was on modelling water and energy fluxes using data from earth observation platforms and automatic weather stations, and validating these models using field campaigns with scintillometry and eddy covariance equipment. This was important to help calibrate models for future applications to enable the determination of ET in these data scarce areas of the Eastern Cape over extended periods. In pursuit of this, the Penman-Monteith (Monteith, 1965) based equations were applied since it is theoretically sound compared to other approaches (Fisher et al., 2008). To gain further insights into the link between dynamics in land cover and ET, a variant of the classical Budyko framework was applied. This was important as it enabled the calibration and benchmarking of the catchment parameter (w) which represents integrated catchment characteristics and this will be useful for future studies. In order to summarise the major findings of the work presented in this thesis, this chapter therefore provides a synthesis of the conclusions that have been drawn from each of the previous chapters. This is followed by a range of recommendations that help to define the future direction of this research. The findings of the research can be summarised focusing on the following key topics:

#### 9.2 Global change impacts on ecosystems function

Drawing from the general introduction in Chapter 1, the drivers of global change are leading to woody encroachment particularly in grasslands. While this may be welcome for carbon sequestration, to the graziers (livestock and wildlife) it implies reduced grazing land as woody thickening impairs undergrowth vegetation such as grass (Jones et al., 2015). The South African government has also recognised these adverse impacts of woody thickening including, the negative effects on hydrological processes (Le Maitre et al., 2015) hence the WfW programme. In order to better manage the invaded landscape, it is important to understand the ways in which the IAPs transform the soil as a substrate for grass production. However, despite huge investment in the WfW programme, there has been moderate progress in clearing even on targeted sites (Beater et al., 2008; McConnachie et al., 2012; van Wilgen et al., 2012). Hence, innovative approaches to clearing are required to better manage the invaded landscape.

In a context of climate change, many parts of the world are becoming increasingly water limited (Kool et al., 2014). Many initiatives for IWRM tend to focus on blue water flows (Hoff et al., 2010) despite that green flows comprise two thirds of total precipitation received over the continents (Liou & Kar, 2014; McMahon et al., 2013). Therefore, future efforts to increase water availability should start with improving green water management and this will be critical in improving global production systems (Hoff et al., 2010; Liu & Yang, 2010). However, the determination of green water flows is challenging despite advancement in the micrometeorology theory and equipment (Amatya et al., 2016). Hence, ET modelling remains critical and the Penman-Monteith (PM) equation provides one of the most theoretically appealing approaches and hence the thesis adopted the PM. However, the biggest challenge in successfully implementing the PM is to determine canopy conductance and the proportion of direct evaporation from the soil  $(E_s)$  and transpiration. Within the purview of environmental changes, it is critical to have an improved understanding of factors modulating the partitioning of energy and water vapour fluxes which in turn influence water and energy balance (Jia et al., 2016; Odongo et al., 2016). Hence, understanding factors influencing energy partitioning may help to optimize the response to projected impacts of climate change. Recent research on the Budyko framework has attempted to determine important catchment characteristics that were ignored by the original framework (Zhang et al., 2001, 2004; Chen et al., 2015; Moussa & Lhomme, 2016). These new insights allowed the Budyko framework to be applicable in nonsteady state situations and in smaller catchments, in order to understand dynamics in catchment water balance. In a context of data scarcity, the new variants of the Budyko frame are useful in

tracing the impact of non-steady state conditions related to catchment characteristics on changes to ET.

#### 9.3 Effects of A. mearnsii invasion on rangeland grass production

The effects of A. mearnsii on soil chemical characteristics and the ability of grasslands cleared of A. mearnsii to recover autogenically were explored. Results suggest that A. mearnsii significantly (p < 0.05) altered the soil chemical characteristics such as on P, CEC, total cations, acid saturation, Mg, P, K, N and pH. Although the soils were generally acidic, pH was even lower in invaded landscape and this has implications on the type of forage that could grow after the removal of A. mearnsii from the rangelands. The results suggest that the ability of the soil to attract positive cations (for example,  $Ca^{2+}$ ,  $Mg^{2+}$ ,  $Na^+$  and  $K^+$ ) improved after the invasion due to increases in CEC and total cations, suggesting that these nutrients could have become more available for production. However, the CEC was relatively low ( $\leq 6 \text{ cmol } L^{-1}$ ), suggesting that the soils have a generally higher sand content and nutrient leaching was a distinct possibility (Aprile & Lorandi, 2012). Such soils require less lime to correct the pH than those with CEC values greater than 6 cmol L<sup>-1</sup>. Differences in N content in invaded and uninvaded sites were indicative of the ability by A. meansii to fix atmospheric nitrogen. Statistically significant differences were also observed with respect to other growth variables (P and K) and these were generally higher in invaded areas, suggesting that once the A. mearnsii is removed, more nutrients will be available to drive biomass production. The principal components analysis (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 clustering of sites according to invasion status, confirmed that the selected soil variables had been changed due to the invasion or clearance of A. mearnsii. However, the simultaneous presence of cleared and invaded sites could be related to the length of time lapsed after clearing, indicating the rehabilitation taking place over time to conditions similar to the pre-invasion period. The predicted ANPP was similar to other estimates in the grasslands, indicating that background production rates could be achieved in the study area even if clearing is not accompanied by other biotic or abiotic interventions to rehabilitate the soil. Results from both soil analysis and biomass modelling suggest autogenic recovery of grasslands after the removal of A. mearnsii in the north Eastern Cape and most of the grazing land lost to IAPs was recovered without further abiotic and biotic modifications of the landscape. This indicates that recovery thresholds for the grassland have not been exceeded. With respect to the DPM, the collected data rejected the widely-held perception that grass biomass production on commercial land will differ substantially from communal areas since grass biomass from the two areas were similar.

The investigation into the effects of *A. mearnsii* on grass production contributed to new knowledge by identifying pathways in which chemical soil properties are modified by the invasion of *A. mearnsii* in the Eastern Cape. These pathways are important as they inform entry points if active rehabilitation is considered in order improve soil chemical characteristics to enhance grass production. In addition, these findings contributed to new knowledge by providing one of the first estimates of grass biomass recovery after the removal of *A. mearnsii* with results suggesting autogenic recovery indicating that abiotic thresholds have not been surpassed.

#### 9.4 Optimal ways of managing IAPs invaded rangelands

The study also sought to understand the biophysical properties (LAI, NDVI and AGB) of A. *mearnsii* in grasslands as they relate to grass production and also to explore possible alternative management options of the invaded landscape. It is envisaged that this understanding could form the basis for future management of infested rangelands. Results suggest that densification of A. mearnsii continues as shown by a high density of small stemmed trees despite clearing by the WfW programme, and use by the local communities for house construction and wood fuel amongst other uses. Average A. mearnsii AGB from all stems was 279 tonnes ha<sup>-1</sup> with larger stems contributing the highest proportion. This high A. mearnsii AGB 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. LAI thresholds for grass production were defined suggesting that good grass production was possible if *A. mearnsii* LAI was kept < 1. Results suggest that ecological thinning could be a viable strategy to promote the two sustainable goals of grass production under the A. mearnsii canopy and carbon sequestration by the woody A. mearnsii. The strong linear relationship developed between NDVI and LAI as well as A. mearnsii AGB could help in targeting areas for thinning using remotely sensed data.

The thesis recommended a radical departure from convention in terms of management of landscape invaded by *A. mearnsii* in South Africa. Current management effort of invaded landscape in South Africa has been clear felling under the auspices of the WfW programme in order to eradicate these plants. However, there has been little progress to this end (Beater et al., 2008; McConnachie et al., 2012; van Wilgen et al., 2012). Hence, reducing *A. mearnsii* canopy LAI through ecological thinning could be critical to enhance multi-benefits of the invaded landscape such as grazing and carbon sequestration. Further, the thesis is also advocating for the recognition of *A. mearnsii* in South Africa as a novel species whose management could resonate well with the ecological thinning recommended. This could also link well with the bio-control method which has been shown to radically reduce seed production (Moran et al., 2013), making thinning a valid optimization of landscape water use to sequestrate carbon, provide shade and grazing, and also wood fuel.

#### 9.5 Dynamics in water vapour and energy fluxes in the Albany Thicket (AT) biome

The strong coupling between rangelands carbon capture process and water use impelled the study to also focus on rangeland energy and ET dynamics. For vegetated land surfaces, ET/ latent heat flux rates are closely related to the carbon fixation rates of plants. It is imperative for water vapour to be lost from leaves during the uptake of CO<sub>2</sub> and hence plants tend to optimise water losses by closing their stomata during dry conditions. Fisher et al. (2011) note that ET estimates provide insights into ecologically important aspects of climate linked to energy supply, water balance and plant productivity. In recognition of this, annual eddy covariance (EC) measurement of water and energy fluxes over the AT dominated by the facultative CAM photosynthesising *P. afra* in the Eastern Cape, South Africa was investigated. Further, factors controlling the partitioning of energy and water vapour fluxes were investigated. These included surface conductance  $(G_s)$ , decoupling coefficient  $(\Omega)$  and Priestley-Taylor coefficient (¥). In addition to post-processing corrections, the EC data were subjected to further quality scrutiny which included flux footprint analysis, site energy balance and co-spectral analysis to enhance better quality of the data. Gap filling data enabled the study to have a continuous ET dataset for over a year. Results showed high ET even during periods of great soil moisture deficit and this may be attributable to the high water storage potential of the P. afra as well as the strong coupling between ground water and the upper layers of the soil. Results also suggest strong biotic control of ET as the relationship between ET and vapour pressure (VPD) revealed and this was consistent with the feedback and feedforward stomatal behaviour reported in literature (Schulze, 1986; Duursma et al., 2014). The negative

relationship between VPD and bulk parameters ( $G_s$ , ¥) also suggests that stomatal conductance was also important in regulating transpiration. The strong couplings between SWC and bulk parameters ( $G_s$  and  $\Omega$ ) suggest strong stomatal and VPD control on the ET process. This was confirmed by the low average  $\Omega$  (< 0.05) observed suggesting that ET was largely controlled by VPD and  $G_s$  and the canopy was strongly coupled with the boundary layer. Average daily latent heat flux (LE) was the smallest flux compared to net radiation ( $R_n$ ) and H throughout the measurement period. Hence, most of the  $R_n$  was consumed by H and this means that ET in the area is essentially water limited since abundant energy was available to drive the turbulent transfers of energy. Biotic factors influenced ET through LAI and the convergent evolution of the AT related to its water storage capacity and the ability of the dominant facultative CAM plants to control stomatal conductance.

The  $\Omega$  was strongly correlated with  $G_s$  but poorly correlated with LAI. Based on the Jarvis & McNaughton (1986)  $G_s$  modelling, this result was not surprising since the MODIS LAI was relatively low (0.1 - 0.8) during the study period. LAI generally provides a surface area for ET to take place. It should be noted that  $G_s$  is a bulk parameter accounting for ET from the surface and the canopy (Monteith, 1965; Leuning et al., 2008) and it is believed to be reflective of canopy conductance in areas with high LAI (Tian et al., 2016). However it is well established that in addition to canopy structure, stomatal conductance is crucial in determining water vapour fluxes (Farquhar & Sharkey, 1982; Schulze, 1986; Schulze et al., 1994). The study area lies over the Albany Thicket which tends to control ET through stomatal behaviour (Mills & Cowling, 2006; Borland et al., 2009; Herrera, 2009). In addition, an examination of daily ET and VPD in this thesis revealed strong stomatal control of the ET process. Therefore, the poor correlation between LAI and bulk parameters was most likely a consequence of the low and generally stable LAI. This may not necessarily be indicative of insignificant contribution to ET from the canopy given that stomatal conductance plays a crucial role in such vegetation that has evolved to avoid drought. Therefore, an understanding of stomatal behaviour is important in order to improve the accounting for water and energy fluxes over vegetated surfaces. LAI may not be a good proxy for transpiration in a context associated with strong stomatal conductance control. However, ¥ was also negatively correlated with VPD suggesting strong influence of SWC to ET. The SWC and canopy development status influenced  $G_s$  which together with VPD determined ET in the study area

The work reported in this thesis provides one of the first long term observation of water and energy vapour fluxes over the AT in South Africa. An understanding of dynamics in water vapour and energy fluxes over this important biome in global change studies was fostered. It is generally believed that the AT Biome is a net carbon sink. It was further demonstrated that the convergent evolution of vegetation in the AT related to a high water storage potential has resulted in more water being available for ET, leading to high pulses of ET even during periods of soil moisture deficit. The thesis has also pioneered the parameterisation of bulk parameters  $(G_s, \notin and \Omega)$  in the AT biome and demonstrated that ET was tightly coupled with VPD and  $G_s$ since  $G_a \gg G_s$ . It has further been noted that an understanding of stomatal behaviour was important in order to improve the accounting for water and energy fluxes over vegetated surfaces.

# 9.6 Application of the Penman-Monteith-Leuning (PML) equation over complex vegetation

Owing to paucity in ET measuring equipment, modelling becomes relevant in helping to understand water use by different landscapes. Hence, the thesis was also devoted to testing the ability of the PML ET model to reproduce observed ET over a system strongly believed to exercise strong control over the ET process through stomatal behaviour. Consequently, the PML was calibrated and validated in the AT Biome of South Africa. The LAI was more responsive to precipitation than SWC indicating the important role of shallow rooted vegetation in influencing ecosystem phenology and in turn water use. It is well established that succulent vegetation have shallow roots and are able to efficiently harvest light and irregular incident precipitation (Borland et al., 2009; Owen et al., 2016). The optimised  $g_{sx}$  was generally low  $(0.0023 - 0.0039 \text{ m s}^{-1})$  although it was comparable to other studies (for example, Leuning et al., 2008). The results were not surprising since it is well established that CAM and facultative CAM plants tend to have low stomata densities and low conductance to water vapour (Borland et al., 2009). This gives credence to the general belief that such facultative CAM vegetation tend to exercise great control of water use (Carr, 2013; Owen et al., 2016). The optimised  $\dot{\alpha}$ was also low in a context of low  $\frac{P}{ET0}$  ratio and this could be a result of the intermittent precipitation as shown from rainfall pattern during the validation periods. The high water content in the plant tissues could have resulted in higher SWC signal recorded by the probe yet in reality the soil could have been dry. In addition, the storage and movement of ground water is one of the least understood part of the hydrological cycle (Jewitt, 2006). As such the measured SWC may not be indicative of precipitation input but strong coupling between the

upper and the lower layers of the soil related to capillary action. All the three approaches of the PML had overestimation bias and this could have been caused by the relatively poor energy balance closure during the validation period, suggesting that the measured latent heat flux was underestimated at the study site. Despite good simulation by the PML approaches, during periods of little precipitation, the approaches underestimated ET. This failure by the approaches could be linked to plant available water and stomatal behaviour. Although SWC could have been low, plant available water to drive ET was high owing to the convergent evolution of the AT vegetation related to great water storage capacity in plant tissues. This is consistent with the pre rainy season greening of vegetation at a time when there is great moisture deficit observed in Africa (Ryan et al., 2016). This greening is not connected to measured soil moisture at the upper layers of soil and hence models based on weather variables and soil moisture are not able to capture changes in leaf phenology which is critical in ET studies. Therefore, the observed trajectories in modelled ET are symptomatic to limitations of the model in areas characterised by strong biotic control of the ET process. In addition, there is a distinct possibility that some of the plants were tapping ground water. Therefore, the observed ET may not be largely connected to SWC at the upper layers of the soil. It was also shown that  $E_s$ dominated total ET and this suggests that there is scope to improve water productivity in the AT and also better management of  $E_s$  can help improve crop yields. The application of the PML helped to better understand the complexities around modelling ET in environments characterised by strong stomatal control of ET and in vegetation that has adapted to avoid droughts through high water storage potential in plant tissues. The thesis also presents one of the first attempts to model ET in the AT in southern Africa.

#### 9.7 Comparison of Penman-Monteith (PM) based equations over grassland

The thesis also compared the performance of the PML and the PMP models over two grasslands sites using a large aperture scintillometer (LAS). Two parameters for the PML,  $\dot{\alpha}$  and  $g_{sx}$  were calibrated for the first time in a South African grassland. Successful calibration hinges on good quality data and as such the adoption of robust data filtering protocols increased the accuracy of ET estimates derived from the LAS. The reliability of the fluxes were also confirmed by the good performance of the PML model on the Truro farm where validation was done using calibrated values of  $\dot{\alpha}$  and  $g_{sx}$  from the Somerton site. Good results were obtained from the application of the three approaches of the PML equation with RMSE ranging from 0.26 – 0.48 mm day<sup>-1</sup>. The good performance of the  $f_{Zhang}$  is encouraging since this has reduced the parameters to be determined in the application of the PML with only  $g_{sx}$  to be parameterised. The PMP did not perform well in both sites and this shows that scaling ET0 to AET through MODIS LAI may not be adequate in areas with low LAI (< 2.5). In addition, the slow response of the MODIS LAI to rainfall events may compound this problem. It was also shown that the PML was sensitive to aerodynamic components over the grasslands suggesting the importance of accurately defining wind speed at the canopy height since failure to do so may lead to gross over or underestimation of ET. Routine meteorological data were able to reproduce fluxes calculated using micrometeorological techniques. This means sparsely distributed weather stations data, when combined with satellite imagery, can confidently be used to derive reasonable ET over wide areas as the validation exercise revealed.

Southern Africa represents one of the regions where there are patchy micrometeorological observation sites. Therefore, successful calibration and good performance of the PML is important since the PML can now be applied over the grassland with reasonable confidence using these derived parameters. This thesis contributed to new knowledge by demonstrating the sensitivity of the PML to aerodynamic conductance. The results revealed that determining accurate wind speed at the canopy height is crucial when working in short vegetation in order to derive reasonable ET estimates using the PML equation. The inadequacy of the PMP to simulate observed ET in the study area confirmed the importance of  $E_s$  in such environments. It was also shown that LAI alone was not good enough in constraining ET0 to AET in areas characterised by short vegetation and low LAI.

#### 9.8 Development of simplified algorithms for estimating ET in drylands

The inadequacy of ET models based on vegetation indices (VI) or LAI in areas with low LAI (< 2.5) was demonstrated in the thesis. Hence, it was prudent to devote some effort to improve the single layer model of PMP by translating it into a two-layer model through the incorporation of a  $E_s$  component. The attempt to improve the PMP was successful as shown by good performance when tested against a LAS and an EC. At the AT site, the model tended to over predict ET like the PML due to a number of factors including poor energy balance closure, overestimation of  $E_s$ , convergent evolution of vegetation in this study site and the intricate links between ground water and upper layers of the soil. The good performance of the proposed algorithm is very important particularly for data scarce areas. The model allows for ET fluxes 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. This work, therefore, has advanced the preliminary

work of Palmer et al. (2014) to develop parsimonious models for predicting ET in data scarce areas at a fine resolution. Attempts to develop simple algorithms for predicting ET based on the relationship between observed ET and vegetation indices (VIs) were unsuccessful and this was not surprising since VIs can neither account for  $E_s$  nor estimate dynamics in stomatal conductance (Glenn et al., 2010). However, robust relations were developed through multivariate regression of ET0 and LAI against observed ET. Uncertainties associated with the proposed algorithm stem from the calculation of f values and general input data. The complexity around the movement of groundwater may introduce errors in the calculation of fvalues. Other uncertainties are linked to the MOD15A2 LAI used since it has been recognised that MODIS tends to overestimate LAI in areas of low LAI (< 0.6). Selection of maximum LAI is also critical and could result in model uncertainties. In situations where disturbance is endemic, use of reported maximum LAI for that vegetation type from elsewhere may be useful. Hence, the thesis contributed to new knowledge by advancing the preliminary work of Palmer et al. (2014) through translating the single layer PMP model to a two layer one. This improved the simulation of ET as was shown by the RMSE. The improved algorithm has the advantage of using data that are available from sparsely distributed weather stations, surface albedo and the LAI to derive ET. In addition, simplified algorithms were developed based on the multivariate regression of ET0 and LAI against observed ET in order to expedite the determination of ET in data scarce areas of the Grassland and AT Biomes. For South Africa, this presented one of the pioneering work in improving parsimonious and accurate algorithms for estimating ET in semi-arid and data scarce areas.

#### 9.9 Impact of land cover change on ET

An understanding of the response of ET to land cover changes related to woody encroachment, settlement and expansion of cultivation on a grassland system is crucial. Using a variant of the Budyko framework (Zhang et al., 2001, 2004; Chen et al., 2015) this link was explored in a South Africa quaternary catchment. Longitudinal analysis of land cover maps at a quaternary catchment scale showed that there were dramatic land cover changes within a 15-year period. This was confirmed by annual changes in the catchment parameter (*w*). Hence, the thesis was successful in showing dynamics in the evaporative index in response to changes in catchment characteristics. The evaporative index was relatively high due to vegetation access to extra water linked possibly, to long roots, runoff and capillary action. It was also shown that that during the years of lower annual mean rainfall the evaporative index for either grassland or woody vegetation cover types tended to be higher. The opposite happened during wetter years

and these patterns were linked to the dynamics in vapour pressure deficits. It was further shown that both local forces related to land cover change and global forces connected to global warming were important in influencing grassland water use.

Therefore, the thesis contributed to new knowledge by applying a variant of the Budyko framework and calibrating the catchment parameter over grasslands affected by IAPs in South Africa and this may be useful for future hydrological studies in similar ungauged catchment. Results also highlighted that understanding ET in grasslands should be informed by an appreciation of local and global processes that modulate water use in the landscape.

#### 9.10 Conclusion

The main essence of this work was to contribute towards better management of rangelands by understanding the dynamics in rangeland grass biomass production and water use. In pursuit of this, the Grassland Biome and the AT Biomes were used as case studies in the development of this thesis. In South Africa, the Grassland Biome is under threat from the invasive *A. mearnsii* while the AT Biome is important in global change studies since it is believed to be a net carbon sink. Based on the results from different objectives in this study, the following were concluded:

- 1. It was shown that *A. mearnsii* canopies affected physico-chemical soil 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.
- 2. Results revealed that across sites, ET was water limited since differences between reference ET and observed ET were large and most of net radiation (R<sub>n</sub>) was consumed by sensible heat flux (H). ET was largely sensitive to VPD and G<sub>s</sub> than to R<sub>n</sub>. This indicates that the canopy was strongly coupled with the boundary layer.
- 3. The PML equation was able to simulate rangeland ET in the Grassland and AT Biomes despite uncertainties connected to the MODIS LAI and surface albedo used to drive the model. However, model limitations were observed in the AT Biome over the *P. afra* canopy. This was caused by the inability to simulate stomatal behaviour and possibly the high plant tissue water storage capacity associated with the AT.
- The study demonstrated that E<sub>s</sub> was dominant in Grasslands and the AT Biomes due to the low LAI (< 2.5) observed. As a result, models that connect potential or reference ET (ET0) to actual ET using VIs or LAI could not adequately reproduce the observed ET.

- 5. Despite changes in the local environment such as catchment characteristics, global forces also affected ET at a local scale. This highlights the need to understand both local and global forces that could affect ET.
- Overall, the study demonstrated that combining remote sensing tools and ground based observations was important to understand rangeland herbage production and water use dynamics.

Looking to the future, global environmental changes such as carbon and nitrogen fertilization as well as climate change have serious implications on the Grassland and AT Biomes. It is projected that carbon and nitrogen fertilization will continue in the future and this has a positive feedback of favouring woody plants encroachment particularly in grasslands (Wigley et al., 2010; Buitenwerf et al., 2012; Stevens et al., 2016). This may further threaten the grasslands since environmental conditions would favour woody vegetation. Consequently, a vicious cycle may play out for farmers since grass biomass production could be undermined as findings from this thesis have shown. This would require innovative rangeland management practices such as the adoption of the 'novel species concept' as the thesis argued. Meanwhile, elevated CO<sub>2</sub> exposure to plants induce a change in leaf structure through changes in stomata openings and a decrease in stomatal density (Woodward & Kelly, 1995; Franks et al. 2013). It has been established that vegetation reduces stomatal conductance at higher atmospheric CO<sub>2</sub> concentration and conversely under reduced concentration, plants increase stomatal conductance (Gedney et al., 2006; Medlyn et al., 2011; Héroult et tal., 2013). This aspect was not addressed in the thesis but requires further consideration in order to identify CO<sub>2</sub> thresholds at which the local ecosystems stomatal conductance could respond to these changes.

The study also highlighted dramatic land cover changes in the Eastern Cape and this has implications on surface albedo which in turn affects energy balance. Elsewhere, it has been established that increasing albedo has a cooling effect on the surface which in turn influence atmospheric turbulence and biogeochemical cycles (Boisier et al., 2013; Houspanossian et al., 2017). However, woody thickening in the socio-ecological system described in this thesis is likely to reduce surface albedo in the long term. Reduced albedo could lead to high available energy leading to the alteration of the energy balance and this may result in the escalation of turbulent processes such as ET.

Climate change scenarios project a general warming in southern Africa, making the region more water limited (Engelbretch et al., 2009). This could lead to landscape becoming unproductive to support current agricultural activities. This necessitates the need for accurately accounting for the so-called 'unproductive' and 'productive' water losses in the landscape. The study showed the dominance of  $E_s$  over transpiration. Hence, the need for encouraging vegetation or crops with high water use efficiency cannot be overemphasised in the light of widespread warming. This suggests the need for more environmental plantings of *P. afra* which will reduce 'unproductive' water use and also sequester more carbon.

The thesis used MODIS LAI and surface albedo in different chapters. Admittedly MODIS LAI has been validated extensively and good results obtained across the globe, but some uncertainties in the MODIS products still remain unresolved (Zhao et al., 2005; McColl et al., 2011; Serbin et al., 2013). In addition, the MOD LAI responds slowly compared to the rapid response of grassland vegetation and this lag time could be resulting in low MODIS LAI values than the actual. Looking to the future, it may be prudent to explore the utility of the Multi-angle Imaging Spectroradiometer (MISR) LAI and surface albedo products in modelling ET. The MISR is an instrument on board the Terra satellite and 'sees' the earth at nine discrete viewing angles and four visible/ near-infrared bands (Hu et al., 2003). However, Fang et al. (2004) observed that the MISR and MOD09 were similar under clear skies but differed in hazy and snow covered regions as well as in shadows. The Albany Thicket is characterised by strong stomatal control to ET but the models applied in this study could not adequately represent stomatal conductance. In generally, LAI presents the surface area over which ET takes place but in vegetation exercising great stomatal control over the ET process, the LAI may not necessarily be reflective of the amount of water evaporated since other factors such as stomata size, density and stomatal conductance become critical (Schulze et al., 1994). This could have undermined some of the results, although there was good agreement between the simulated and observed ET. Furthermore, the study had a small database particularly over the grassland for computing ET. It was going to be worthwhile to have a long-term database for calibrating and validating ET models. This could have affected the calibration of the minimum and maximum fraction (f) of  $E_s$  especially when the  $f_{SWC}$  was applied. Although the small database could have undermined the results, there was good agreement between the observed and predicted ET. With respect to the soil variables analysed, it was going to be more useful if more biotic and physical soil characteristics were analysed in order to have a broader picture of soil transformation after the invasion or removal of A. mearnsii. However, the physico-chemical

properties analysed are key indicators of landscape recovery or deterioration (Costantini et al., 2016)

## 9.11 Challenges faced during the course of this research

- Selection of appropriate sites for installing the LAS and EC equipment for data validation was quite a challenge. The sites had to be within the study area and safe from human, livestock and wildlife interference and also have cellular phone signal to allow for communicating with the equipment. Although, better sites were found in commercial farms, meeting all these conditions was difficult. For example, the LAS was occasionally knocked down by livestock and interfered with by humans. However, online monitoring of the equipment helped in early detection of the problems and hence reducing data loss. With respect to the EC a suitable area was found in a game reserve that did not receive cellular phone signal. Fortunately, the EC functioned relatively well throughout the observation period and the equipment was fenced off to preclude wildlife. The fine wire thermocouples of the EC frequently broke down and had to be replaced. During periods with no fine wire, the sonic temperature was used in the calculation of fluxes. As a result, the financial costs for monitoring and maintaining the LAS and EC were high.
- Owing to logistical challenges, a field campaign approach was adopted for collecting ET data from the Grassland Biome. Despite this, the models were successfully calibrated and validated in the biome.
- The unavailability of the 2015 and 2016 MOD16 ET product has undermined efforts to validate the model in the study sites using data generated from the LAS and EC.

## 9.12 Recommendations for future research

The work presented in this thesis and the knowledge acquired of the research area has highlighted the following for further consideration:

- It was highlighted in the thesis that IAPs such *A. mearnsii* significantly altered physicochemical soil properties. Therefore, it will be prudent to conduct further research to establish the extent to which the physico-chemical soil properties alteration pathways identified in this thesis could be used as entry points for rehabilitating areas cleared of *A. mearnsii*. This may also involve conducting a lime application trial and it might be useful to compare aided and unaided recovery of grasslands after the removal of IAPs.
- Results suggest that ecological thinning of *A. mearnsii* could be useful in enhancing grass production and promoting carbon sequestration by the woody *A. mearnsii* in

rangelands. These are two important sustainable development goals for increasing food production and carbon sequestration in light of climate change. It was further demonstrated that as a result of *A. mearnsii* invasion, soil pH declines and nitrogen increases, and this, together with the very high leaf area index, negatively affects understorey vegetative cover. Multiple uses of *A. mearnsii*, including chip board, housing material, wood-fuel and potential for biofuel were also reported. Therefore, it would be prudent to test through experimental work whether the creation of an artificial savanna leaving large *A. mearnsii* trees with grasslands that are useful as grazing grounds could, indeed be an optimal solution for managing the invaded landscape. This may also help to highlight the influence of thinning on allelopathic effects of *A. mearnsii*.

- It was demonstrated that the convergent evolution of vegetation in the AT related to a high water storage potential has resulted in more water being available for ET, leading to pulses of high ET even during periods of soil moisture deficit and this also makes ET modelling in the AT quite challenging. Therefore, it will be vital to establish the extent to which the observed ET is being driven by water stored in plant tissues, SWC and capillary action. The use of isotopes and monitoring SWC at different depths may be useful starting points.
- The study also successfully calibrated surface and stomatal conductance in the Grassland and AT Biomes. These parameters are critical to the implementation of the PM equation which is considered to be one of the most theoretically sound model for deriving AET. The PM equation is essentially driven by meteorological data, surface albedo and the LAI and with the sparsely distributed weather stations, the approach may be useful in deriving ET using locally calibrated parameters. Therefore, future research may focus on calibrating the model across all biomes in South Africa
- Although remote sensing models (for example, Bastiaanssen et al., 1998; Mu et al., 2011) are available to provide spatial variation in ET, it is more useful to validate such models using ground-based techniques such as LAS and EC. Therefore, the measured ET data from this thesis provide an opportunity for comparing remotely sensed ET with that measured *in situ*.
- A new parsimonious ET model was described and validated in the thesis, thereby advancing the work of Palmer et al. (2014). It will be necessary to apply the model and validate it across the other biomes in southern Africa. The model has the advantage of

only using meteorological data available at weather station, LAI and surface albedo and does not need fine tuning with observed data.

• Recent variants of the Budyko framework provide an opportunity to interrogate the link between land cover change and hydrological fluxes using data that can be easily obtained. The thesis parameterised the catchment parameter (*w*) which is indicative of the integrated impact of different catchment variables and is essentially reflective to the influence of land cover on hydrological fluxes. Therefore, calibrating the *w* parameter across the catchments will be useful in tracking dynamics in land cover and its consequences on hydrological fluxes.

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# **APPENDIX A: SUPPLEMENTARY DATA FOR CHAPTER 2**

	Initial Eigenvalues				
Component	Total	Percentage of Variance	Cumulative percentage		
1	4.229	38.444	38.444		
2	2.673	24.303	62.747		
3	1.350	12.269	75.016		
4	0. 850	7.730	82.746		
5	0.560	5.093	87.839		
6	0.474	4.311	92.150		
7	0.356	3.239	95.389		
8	0.281	2.554	97.942		
9	0.196	1.785	99.727		
10	0.030	.273	100.000		
11	6.116E-06	5.560E-05	100.000		

Table A.1.	Total	variance	explained	bv	each	com	ponent.
			•••••••••••	~ ,		••••	

Table A.2. Communalities table.

	Communalities		
	Initial	Extraction	
Bulk density (g mL <sup>-1</sup> )	1	0.55	
$P(mg L^{-1})$	1	0.54	
$K (mg L^{-1})$	1	0.64	
Ca (mg L <sup>-1</sup> )	1	0.87	
$Mg (mg L^{-1})$	1	0.74	
CEC (cmol $L^{-1}$ )	1	0.94	
Total cations (cmol L <sup>-1</sup> )	1	0.86	
Acid saturation (%)	1	0.95	
pH (KCl)	1	0.77	
Zn (mg L <sup>-1</sup> )	1	0.63	
N (kg ha <sup>-1</sup> )	1	0.77	
N (kg ha <sup>-1</sup> )	1	0.77	

	Components		
Soil variables	1	2	3
Bulk density (g	0.03	0.03	0.74
mL <sup>-1</sup> )			
$P(mg L^{-1})$	0.03	0.72	-0.16
K (mg L <sup>-1</sup> )	0.78	0.03	0.15
Ca (mg L <sup>-1</sup> )	0.92	-0.14	-0.07
Mg (mg L <sup>-1</sup> )	0.82	-0.20	-0.153
CEC (cmol L <sup>-1</sup> )	-0.46	0.79	0.33
Total cations	0.65	0.61	0.25
$(\text{cmol } L^{-1})$			
Acid saturation	-0.85	0.42	0.19
(%)			
pH (KCl)	0.27	-0.84	-0.012
$Zn (mg L^{-1})$	0.36	0.43	-0.56
N (kg ha <sup>-1</sup> )	0.61	0.29	0.55

Table A.3. Rotated Component matrix.

## **APPENDIX B: METEOROLOGICAL DATA**

#### Derivation of other meteorological data

The meteorological parameters required for modelling ET include solar radiation ( $R_s$ ), temperature, relative humidity (RH), atmospheric pressure, wind speed and rainfall. Mean daily temperature, rainfall, wind speed and RH were computed from hourly daily data. The derivation of these data has been described in the thesis. This section provides logistics for deriving the variables that were not extensively described (pressure, psychrometric constant, vapour pressure, slope of saturation vapour pressure) and also the gap filling approaches applied for missing meteorological data.

### Atmospheric pressure

The atmospheric pressure is required in the calculation of ET. Variation in atmospheric pressure across an altitudinal is negligible and hence in the calculation of ET, the average value for a location is sufficient and for this study pressure was calculated as in Allen et al., (1998):

$$P = 101.3 \left(\frac{293 - 0.0065z}{293}\right)^{5.26}$$
[B.1]

where P is atmospheric pressure (kPa),

z is elevation above sea level (m)

#### **Psychrometric constant**

The psychrometric constant ( $\gamma$ ) relates the partial pressure of water in air to the air temperature and it was calculated (Allen et al., 1998):

$$\gamma = \frac{c_{\rho}P}{\epsilon \lambda} = 0.6665 * 10^{-3}P$$
[B.2]

where  $\gamma$  is psychrometric constant, P is atmospheric pressure (kPa),  $\lambda$  is latent heat of evaporation (2.45MJ kg<sup>-1</sup>),  $c_{\rho}$  is specific heat at constant pressure,  $\in$  is ratio of molecular weight of water vapor/ dry air = 0.622

The availability of temperature and relative hunidity (RH) data enabled the calculation of saturation  $(e_s)$  and actual  $(e_a)$  vapour pressure, slope of saturation vapour pressure curve ( $\Delta$ ) and vapour pressure deficit (VPD) which are required parameters in the Penman-Monteith formulation.

## Saturation vapour pressure

This occurs when air is enclosed above an evaporating water surface, such that equilibrium is reached between the water molecules escaping and returning to the water reservoir. ( $e_s$ ). Higher air temperature results in a higher storage capacity leading to a higher saturation vapour. Mean saturation vapour pressure ( $e_s$ ) was calculated as:

$$e_s = \frac{e^0(T_{max}) + e^0(T_{min})}{2}$$
 [B.3]

where  $e^{0}(T) = 0.6108 \exp \frac{17.27 T}{T + 237.3}$  and *T* is air temperature (°C)

#### Actual vapour pressure

The actual vapour pressure  $(e_a)$  is the vapour pressure exerted by the water in the air. When the air is not saturated, the actual vapour pressure will be lower than the saturation vapour pressure. Actual vapour pressure was calculated as:

$$e_a = e^0(T_{min})\frac{RH_{max}}{100} + (T_{max})\frac{RH_{min}}{100}$$
 [B.4]

where  $e_a$  is actual vapour pressure,  $e^0(T_{max})$  is saturation vapour pressure at daily maximum temperature (kPa),  $e^0(T_{min})$  is saturation vapour pressure at daily minimum temperature (kPa),  $RH_{max}$  and  $RH_{min}$  are maximum and minimum relative humidity(%).

### Slope of saturation vapour pressure curve

For determining ET the slope of the relationship between  $e_s$  and T ( $\Delta$ ) is required and this was derived as follows:

$$\Delta = 4098 \frac{\left[0.6108 \exp\left(\frac{17.27 T}{T+237.3}\right)\right]}{(T+237.3)^2}$$
[B.5]

### Gap filling missing meteorological data

Since the PML and PMP models are mainly driven by meteorological data from local weather stations, accurate data is crucial for their successful implementation. Where data were missing, gap filling was done using robust methodologies.

#### Solar radiation $(R_s)$

If the  $R_s$  was missing, the records from the nearby stations were used. If these were also missing, the Angstrom formula, which relates solar radiation to extra-terrestrial radiation and relative sunshine duration was applied (Allen et al., 1998):

$$R_s = a_s + b_s \frac{n}{N} R_a \tag{B.6}$$

where is  $R_s$  is solar radiation (MJ m<sup>-2</sup> day<sup>-1</sup>), n is actual duration of sunshine (hour), N is maximum possible duration of sunshine or day light hours (hour), given by  $N = \frac{24}{\pi} \omega_s$  where  $\omega_s$  is the sunset hour angle and  $\frac{n}{N}$  is relative sunshine duration,  $R_a$  is extraterrestrial radiation,  $a_s + b_s$  is a fraction of extraterrestrial radiation reaching the earth on clear days (n = N), where no actual solar radiation data are available and no calibration has been carried out for improved  $a_s + b_s$  parameters, the value  $a_s = 0.25$  and  $b_s = 0.50$  were used (Allen et al., 1998).

### Other missing meteorological data: method of cumulative residuals/ ellipse test

One of the recommended methods of filling meteorological data in computing ET is the method of cumulative residuals (Allen, 1998; Costa & Soares, 2009) which is 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 adjacent stations within the same climatic region. The candidate series can be considered similar if the cumulative residuals are not biased and pass the ellipse test. 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 now 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 and then run regression and the developed equation is then used to fill the data. An illustration with respect to maximum temperature (Tmax) is provided for the Somerton study site using data from the weather station at Ugie, Eastern Cape, South Africa (Fig. B.1).



Figure B.1a. Ellipse test on maximum temperature (Tmax).



Figure B.1b. Regression equation for predicting Tmax at Somerton farm

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# **APPENDIX C: LAI EXTRACTION**

The flow diagram shows the procedure adopted in extracting LAI from the MOD15A2 product in ArcGIS version® 10.2.



# **APPENDIX D: ALBEDO EXTRACTION**

The flow diagrams show the procedure adopted in extracting surface albedo from the MCB43 product in ArcGIS version® 10.2.



## APPENDIX E: R SCRIPT FOR RUNNING THE PML AND OPTIMIZATION MODEL

This section provides an example of an R script used for computing ET and subsequent parameter estimation using *rgenoud* package.

#Read data

```
evaporate.data=data.frame(read.csv("evaporate.csv",header=T))
```

# Print the data frame to the screen evaporate.data

## Calculate actual vapor pressure (ea)
eTmin <- function(Tmin)</pre>

eTmin = 0.6108\*exp(17.27\*Tmin/(Tmin+273.3)) return(eTmin)

evaporate.data\$eTmin = eTmin(evaporate.data\$Tmin)

evaporate.data

# Define a function to calculate eTmax eTmax <- function(Tmax) eTmax=0.6108\*exp(17.27\*Tmax/(Tmax+273.3)) return(eTmax) evaporate.data\$eTmax = eTmax(evaporate.data\$Tmax)

evaporate.data

# calculate ea based on air temperature and add to data frame

#Define a function to calculate ea

#Define a function to calculate mean air temperature (Tmean)

evaporate.data\$Tmean = (evaporate.data\$Tmax+ evaporate.data\$Tmin)/2

evaporate.data

#Define a function to calculate delta-slope of curve relating saturation vapour pressure to temperature(de/dT)

# calculate atmospheric pressure(P)

evaporate.data\$P = 101.3\*((293-0.0065\* evaporate.data\$elev)/(293))^5.26

#calculate gamma-psychrometric constant
#gamma = 0.665\*10^-3\*P

evaporate.data gamma = 0.665\*10^-3\* evaporate.data P

evaporate.data

#calculate slope of curve relating saturation
evaporate.data\$E = evaporate.data\$delta/ evaporate.data\$gamma

evaporate.data

# calculate friction velocity (k2um)
evaporate.data\$friction = evaporate.data\$Windspeed\*0.41^2

evaporate.data

#Define a function to calculate fdrying

#calculate fdrying

evaporate.data

## **OPTIMIZATION FUNCTION**

F<- function(ET, las){
F= sum(abs(evaporate.data\$ET- evaporate.data\$las))/118
return(F)
}
evaporate.data\$output= genoud (fn=F, nvars=2
max = FALSE, pop.size = 100, max.generations = 300,
wait.generations = 100, hard.generation.limit = TRUE,
starting.values = evaporate.data\$gsx, evaporate.data\$gsx\$alphaMemoryMatrix = TRUE,</pre>

Domains = matrix(c(0.002, 0.1, 0.02, 1), nrow=2, ncol=2), default.domains=10,

solution.tolerance = 0.001, gr = NULL, boundary.enforcement = 0,

lexical = FALSE, gradient.check = TRUE, BFGS = TRUE, data.type.int = FALSE,

hessian = FALSE, unif.seed = 812821, int.seed = 53058, print.level = 2,

share.type = 0, instance.number = 0, output.path = "stdout",

output.append = FALSE, project.path = NULL, P1 = 50, P2 = 50,

P3 = 50, P4 = 50, P5 = 50, P6 = 50, P7 = 50, P8 = 50, P9 = 0,

P9mix = NULL, BFGSburnin = 0, BFGSfn = NULL, BFGShelp = NULL,

control = list(), optim.method=ifelse(evaporate.data\$boundary.enforcement< 2,

BFGS", "L-BFGS-B"), transform = FALSE, debug = FALSE,

cluster = FALSE, balance = FALSE)