Department of Plant Production and Agroecology in the Tropics and Subtropics

University of Hohenheim Crop Water Stress Management in the Tropics and Subtropics

Prof. Dr. Folkard Asch

A Study of Pasture Cropping as an Alternative Cropping System for Sub-Saharan Africa

Dissertation

Submitted in fulfilment of the requirements for the degree

‘Doktor der Agrarwissenschaften’

(Dr. sc. agr. /Ph.D. in Agricultural Sciences)

to the Faculty of the Agricultural Sciences

presented by

Rohan Orford

South Africa

2019

This thesis titled “A Study of Pasture Cropping as an Alternative Cropping System for Sub-Saharan Africa” was accepted as doctoral dissertation in fulfilment of requirements for the degree ‘Doktor der Agrarwissenscheaften’ by the Faculty of Agricultural Sciences at University of Hohenheim on 25/09/2019.

Date of oral examination: **7 Feb 2020**

Examination committee

Supervisor and Reviewer	Prof. Dr. Folkard Asch
Co-Reviewer	Prof. Dr. Michael van Der Laan
Additional Examiner	Prof. Dr. Georg Cadisch & Prof. Dr. John Annandale
Vice-Dean and Head of Committee	Prof. Dr. Doluschitz

Acknowledgments and Funding

I would like to acknowledge in no particular order the various organisations listed below who provided me with the resources and belief to make this study possible.

Eiselen Foundation

DAAD (Deutscher Akademischer Austauschdienst – German Academic Exchange Service)

CFH (Conservation, Food and Health)

NRF (National Research Foundation – South Africa)

Food Security Centre- Hohenheim of Hohenheim

Department of Plant and Soil Science-University of Pretoria

CONSERVATION, FOOD & HEALTH FOUNDATION
DAAD
Foundation fiat panis
NRF National Research Foundation
FSC Food Security Center
UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Preface

This study would not have been made possible without the support of many people! I would firstly like to thank my supervisor Prof. Dr. Folkard Asch who believed in my project enough to make it possible and provided the platform and the patience to let me achieve this. His team including Sabine Stürz, Marcus Giese, Holger Brueck, Gabriele Schmid and all the FSC staff such as Detlef Virchow, Brigitte Kranz and Hélène Stauss and colleagues who provided support and companionship over the PhD. Thank You.

In South Africa, I would especially like to thank the University of Pretoria who welcomed me with open arms to be part of their institution. In particular Prof John Annandale who believed in me from the beginning and enriched my abilities as a scientist for my PhD and opened the world of intense biophysics and crop modelling to me. Thank you for expecting nothing less from me. The application and success of my PhD would never have been possible without Prof. Michael van der Laan who was a major support to me academically, in the modelling process and as a friend. I would also like to thank Dr. Nicky Taylor and Dr. Wayne Truter for offering resources as support and always being there for a hot or cold beverage. I also want to thank the wonderful support that was offered by Leane van Zyl who supported me with her epic efficiency. Ronnie Gilfillan as my friend and for a good chat. I also want to thank Diana Marais, Burger Cillie, Shoba Govender, Charl Hertzog and all the Hatfield staff for all the support.

My parents also made all this possible offering belief, motivation and enthusiastic support. Finally, last but not least I want to thank my wife Emma for nothing short of everything.

Table of Contents

List of Figures

List of Tables

Abbreviations

Symbol	**Unit**	**Description**
∆SW	Vol % or mm	Change in soil water
1D		One dimensional
AI		Aridity index
ANOVA		Analysis of variance
CM		Cowpea monocrop
CA		Conservation agriculture
CanopyInt		Rain interception
Cb		Competitive ability
CombinedPET	mm	Maximum potential evapotranspiration
CombinedPT	mm	Combined transpiration of two crops
CV	%	Coefficient of variation
Cr		Competitive ratio
Cs		Competitive severity
DAP		Days after planting
DM	tons ha-1	Dry matter
ETo	mm	Evapotranspiration
FC	%	Field capacity
FI	%	Fractional interception of radiation
FItransp		Fractional interception of radiation by photosynthetically active leaves

HI	%	Harvest index
I	mm	Irrigation
Kc		Crop Coefficient
LAI	m^2m^{-2}	Leaf area index
LER		Land equivalent ratio
LERi		Land equivalent ratio per crop i
LERplot		Land equivalent ratio at a plot scale
MAE		Mean absolute error
PM		Established pasture monocrop
P	mm	Precipitation
PaCr		Pasture cropping
PET	mm	Seasonal potential evapotranspiration
Pi		Proportion
PotEvap	mm	Evaporation
Rc		Resource complementarity
RMSE		Root mean square error
RWH		Rainwater harvesting methods
SLA		Specific leaf area
Soil.InterDOY		Daily Rain interception
SSA		Sub-Saharan Africa
SW	mm/m	Soil water
SWB		Soil Water Balance model
TDM at emergence	g m2	Initial biomass
TransFactor		Transpiration factor
VPD	kPa	Vapour pressure deficit
WP	%	Wilting point
WUE	$\mathrm{kg\ mm^{-1}ha^{-1}}$	Water use efficiency
Yi	Tons ha^{-1}	Yield

Summary

With food security and soil degradation being a major concern and hurdle in the development goals of sub-Saharan Africa (SSA), there has been and continues to be an attempt to find an alternative cropping system to conventional monocropping that rehabilitates soils whilst increasing productivity and efficiency of the subsistence cropping system. Such a cropping system needs to be realistically adoptable within the SSA social and ecological constraints. An alternative Australian winter rainfall relay cropping system coined pasture cropping (PaCr) was identified as an option that may surmount some of these limitations. This research involved completing a field trial through to model scale introductory assessment of the water dynamics in PaCr and the implications thereof in yield, water use efficiency (WUE) and competition for water; ultimately assessing the potential of PaCr in SSA. PaCr was adapted to an intercropping system for SSA summer rainfall conditions. The three treatments included the representative subsistence crop cowpea (*Vigna unguiculate)* and a common indigenous pasture (*Eragrostis curvula)* and an additive PaCr setup of cowpea directly seeded into pasture in water limited (rainfed) field trials in Pretoria, South Africa between 2013-2015. The DM yields of PaCr were 17% and 293% higher in both seasons compared to the conventional cowpea monocrop yield. When comparing PaCr yield to conventional pasture, there was a 12% and 89% higher yield in both seasons compared to the conventional pasture monocrop yield. The greater yield advantage in 2015 with the limited rainfall indicates that PaCr was most advantageous in terms of DM yield in a drier year which is a time of greatest risk and food insecurity. PaCr was also more WUE in both seasons, being significantly higher than the cowpea monocrop in 2015. Competition also showed a higher degree of competitiveness by cowpea in the wetter 2013-14 season and lower competitive ability in the drier 2015, whereas pasture showed little competitive response in 2013-14 and attaining significantly higher yields than the monocrop in 2015. The results of the field trials were used to adapt the University of Pretoria's Soil Water Balance (SWBsci) crop model to simulate an intercropping system. Observed field results were compared to simulated results and statistical goodness of fit indicators were assessed, concluding that with all the variations of season and systems, the results were acceptable as an inaugural adaptation of the Soil Water Balance model. Other relevant crop water use parameters were extrapolated from the simulated data allowing for a more complete insight into the field trials. With the adapted SWBsci model, 14-year simulations were run in three different climates and on three different soil types for all three cropping systems to map out the viability of PaCr across an aridity index continuum as a reference for further application in research or in industry and to stress test SWBsci. Results demonstrated that PaCr was only advantageous in dry sub-humid to humid conditions on clay-loam to sandy soils, whereas pasture was dominant in more semi-arid conditions on the three different soils. Cowpea only performed better on clay soils in dry-sub humid to sub humid conditions. These advantages are attributed to differing plant water availability at various root depths suiting growth and/or competition of either one or both crops. These plant water availability differences were determined by water holding capacity of various soil types and rainfall volumes.

From a WUE perspective, the pasture and PaCr did have a higher WUE but with the extreme variation in rainfall there was no significant difference. But pasture and PaCr both had a very high WUE in arid to semi-arid conditions due to the deeper roots of pasture accessing stored soil water. Competition also showed insignificant results due to the variation in the rainfall. However, in more arid to semi-arid conditions on clay-loam and sand competition outweighed facilitation thus resulting in land equivalent ratios (LER) of below 1, whereas on clay for the same aridity levels the average LER was greater than one. This was attributed to cowpea have a better competitive ability when clay water holding capacity confined plant available water to the top soil layers. The converse is true in the dry sub-humid conditions and wetter conditions because LER was less than one on clay soils while being greater than one on clay-loam and sand. This was attributed to the lower water holding capacity of sand spreading the plant available water through the profile allowing for niche root partitioning to be effective.

For subsistence farmers, PaCr out-yielded the cowpea monocrop in arid conditions on all three soil types and on clay in semi-arid conditions. In the wetter dry sub-humid conditions, PaCr out-yielded cowpea on sand. In the wet sub-humid conditions PaCr does well on clay-loam and sand, but cowpea yields under these conditions are more than adequate to make the choice of PaCr debatable form a yield point of view. However, if soil rehabilitation is a necessity in the sub-humid areas, this makes PaCr a very realistic option.

Zusammenfassung

Da die Ernährungssicherheit und die Bodendegradation ein Hauptanliegen und eine Hürde für die Entwicklungsziele des subsaharischen Afrikas (SSA) darstellen, wurde und wird versucht, ein alternatives Anbausystem zum konventionellen Monokulturanbau zu finden, das die Böden rehabilitiert und gleichzeitig die Produktivität und Effizienz des Subsistenzsystems erhöht. Ein solches Anbausystem muss realistisch an die sozialen und ökologischen Gegebenheiten der SSA angepasst werden können. Für die vorliegende Forschungsarbeit wurde als eine Option, die einige dieser Einschränkungen überwinden könnte, ein alternatives Australisches Winterregenrelais-Erntesystem für das Ernten von Weideflächen (PaCr) identifiziert. Die Forschung beinhaltete den Abschluss eines Feldversuchs bis hin zur modellhaften einleitenden Bewertung der Wasserdynamik bei PaCr und deren Auswirkungen auf Ertrag, Wassernutzungseffizienz (WUE) und Wettbewerb um Wasser. Abschließend wurde das Potenzial von PaCr in SSA bewertet. PaCr wurde an ein Mischkultur für SSA Sommerregenbedingungen angepasst. Die drei Versuche umfassten die repräsentative Subsistenzpflanze Augenbohne (Vigna unguiculate) und eine gemeinsame einheimische Weide (*Eragrostis curvula*) sowie einen zusätzlichen PaCr-Aufbau von Augenbohne, die in wasserlimitierten Feldversuchen in Pretoria, Südafrika, zwischen 2013-2015 direkt in die Weide gesät wurde. Die Trockenmasse-Erträge von PaCr lagen in beiden Jahreszeiten um 17% bzw. 293% höher als die konventionelle Monokultur-Erträge von Augenbohne. Vergleicht man den PaCr-Ertrag mit dem konventionellen Weidenanbau, so ergibt sich in beiden Jahreszeiten ein um 12% bzw. 89% höherer Ertrag im Vergleich zum konventionellen Monokultur-Ertrag. Der größere Ertragsvorteil im Jahr 2015 mit den begrenzten Niederschlägen zeigt, dass PaCr in einem trockeneren Jahr, welches das größte Risiko unter Gesichtspunkten der Ernährungssicherheit darstellt, in Bezug auf den DM-Ertrag am vorteilhaftesten war. PaCr war in beiden Jahreszeiten auch wassernutzungseffizienter und lag damit deutlich über der Augenbohne-Monokultur im Jahr 2015. Der Wettbewerb zeigte auch ein höheres Maß an Wettbewerbsfähigkeit der Augenbohne in der feuchteren Saison 2013-14 und eine geringere Wettbewerbsfähigkeit in der trockeneren Jahreszeit 2015, während die Weide im Zeitraum 2013-14 wenig wettbewerbsorientiert reagierte und im Jahr 2015 deutlichen Mehrertrag aufwies. Die Ergebnisse der Feldversuche wurden genutzt, um das Bodenwasserhaushaltsmodell (SWBsci) der Universität Pretoria an die Simulation eines Zwischenfruchtsystems anzupassen. Die beobachteten Feldergebnisse wurden mit den simulierten Ergebnissen verglichen und die statistische Güte der Anpassungsindikatoren bewertet, was zu dem Schluss führte, dass die Ergebnisse bei allen Variationen der Saison und der Systeme als erste Anpassung des Bodenwasserhaushaltsmodells akzeptabel waren. Andere relevante Parameter der Pflanzenwassernutzung wurden aus den simulierten Daten extrapoliert, was einen umfassenderen Einblick in die Feldversuche ermöglichte. Mit dem angepassten SWBsci-Modell wurden 14-jährige Simulationen in drei verschiedenen Klimazonen und auf drei verschiedenen Bodentypen für alle drei Anbausysteme durchgeführt, um die Lebensfähigkeit von PaCr über ein Trockenindexkontinuum hinweg als Referenz für die weitere Anwendung in Forschung oder Industrie

und für den Stresstest von SWBsci zu ermitteln. Die Ergebnisse zeigten, dass PaCr nur bei trockenen, subhumiden bis feuchten Bedingungen auf Lehm- und Sandböden von Vorteil war, während Weiden bei eher semi-ariden Bedingungen auf den drei verschiedenen Böden dominierten. Augenbohne schnitten nur auf Tonböden in trockenem, feuchtem bis subfeuchtem Untergrund besser ab.

Aus WUE-Sicht hatten Weide und PaCr zwar einen höheren WUE-Wert, aber mit den extremen Niederschlagsschwankungen gab es keinen signifikanten Unterschied. Aber Weide und PaCr hatten beide eine sehr hohe WUE bei trockenen bis semi-ariden Bedingungen, da die tieferen Wurzeln der Weide auf gespeichertes Bodenwasser zurückgreifen können. Auch der Wettbewerb zeigte aufgrund der unterschiedlichen Niederschläge nicht signifikante Ergebnisse. Bei trockeneren bis halbtrockeneren Bedingungen auf Ton-Lehm und Sand überwog jedoch die Konkurrenz die Erleichterung (?), so dass die Flächenäquivalenzverhältnisse (LER) unter eins lagen, während bei Ton bei gleichen Trockenheitswerten der durchschnittliche LER-Wert größer als eins war. Der Umkehrschluss gilt für die trockenen, subhumiden und feuchteren Bedingungen, da LER auf Lehmböden weniger als eins war, während es auf Ton-Lehm und Sand höher als eins ergab.

Für Subsistenzbauern brachte PaCr in trockenen Bedingungen auf allen drei Bodentypen und auf Ton in semi-ariden Bedingungen einen höheren Ertrag als die Monokultur der Augenbohne hervor. Auf Sand erzielte PaCr ebenfalls einen höheren Ertrag als die Monokultur unter den feuchteren, trockenen, subhumiden Bedingungen. Bei nassen, subhumiden Verhältnissen waren die Ertragsunterschiede zwischen PaCr und der Monokultur der Augenbohne nicht signifikant. Sollte jedoch die Bodensanierung im Vordergrund stehen, stellt PaCr eine bessere Alternative dar.

1. General Introduction

Food security in semi-arid systems in sub-Saharan Africa (SSA) has been identified as amongst the worst in the world (Rockström and Falkenmark, 2000). Despite efforts during the Green Revolution of the 1960-70's, high population growth rates are outstripping stagnating increases in land productivity which is compensated for not by intensification, but rather by the expansion of cultivated land into rangeland and savannah ecosystems in a process of "extensification", enlarging the area of degradation and biodiversity loss (Winterbottom et al., 2013). These newly cultivated lands are thus lost as an alternate grazing area during the dry season when marginal grazing land cannot sustain herds and eventually leads to overgrazing and the subsequent increased potential for conflict between pastoralists and agriculturalists (LEAD, 2006). "Extensification" has caused 65% of the arable land, 30% of the rangeland and 20% of the forests in Africa to be degraded for which 80% of the degradation is due to tillage and overgrazing (Glatzel et al., 2014; Ifad, 2013). This is said to have contributed to the reduced net primary productivity (kg C $ha^{-1}year^{-1}$) by more than 40% in the last two decades whilst the population has doubled (see figure Figure 1-1) (Nkonya, Gerber, von Braun, De Pinto, & Braun, 2011). Furthermore, the chronic and extensive ecosystem degradation has reduced agroecosystem resilience and resource use efficiency, exposing subsistence farmers to unprecedented levels of risk (Folke et al., 2004; Glatzel, Conway, Alpert, & Brittain, 2014).

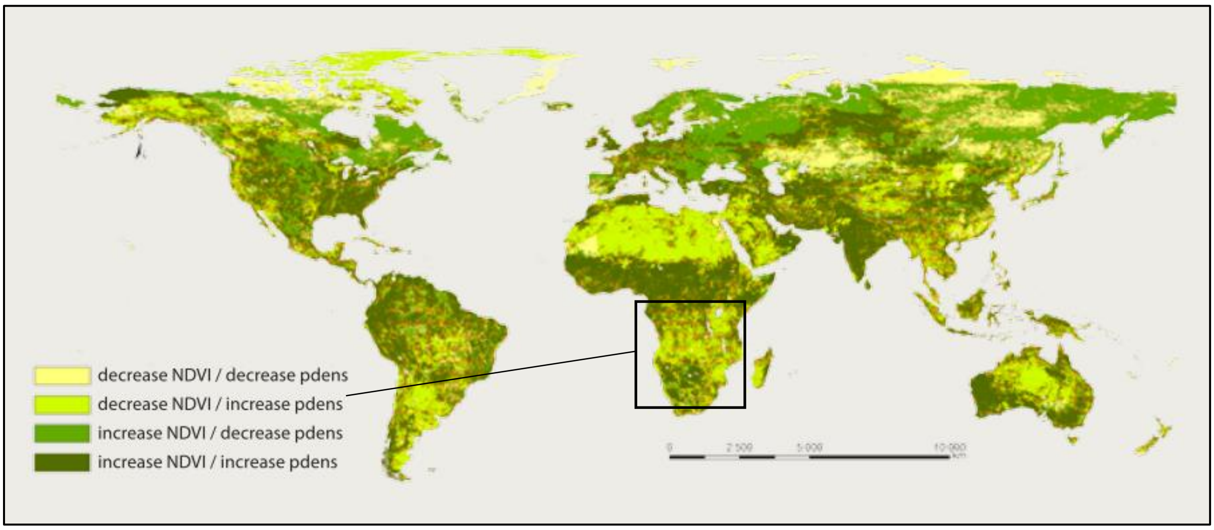


Figure 1-1 Relationship between change of population density and greenness (as measured by NDVI), 1981–2006 decrease. Note that sub-Saharan Africa is clearly showing a decrease in NDVI with increased population density (pdens) (Nkonya et al., 2011).

Intercropping, conservation agriculture (CA), various rainwater harvesting (RWH) methods and mulching have been put forward as ways of achieving sustainable intensification by improving production, water use efficiency (WUE) and rehabilitation of soils, achieving varying degrees of success (Hatfield, Sauer, & Prueger, 2001; Schultze-Kraft et al., 2018; Valbuena et al., 2012; Vohland

& Barry, 2009). The trade-off with mulching is that most of the mulching material is commonly used for feed and/or is traded or used for fuel, construction or burnt, with nothing remaining to maintain soil fertility (Valbuena et al., 2012). With livestock being a primary asset, feed for livestock most often takes priority over mulching. No rainwater harvesting system fulfils all the simultaneous requirements of improving WUE and land productivity of forage and food for people simultaneously; reducing the risk of cropping system failure and rehabilitating the soil and ecosystem all within the constraints of a low input marginalised rural setting. Furthermore, very few rainwater harvesting systems are socially or economically attractive enough to incentivise adoption (Vohland & Barry, 2009). However, outside the realm of conventional crops, pasture does have many qualities that can fulfil the requirements listed.

Drought tolerant, indigenous tropical and sub-tropical perennial grasses, preferably of a high forage quality and grazed in-situ can fulfil improving WUE and land productivity whilst rehabilitating the soil and ecosystem all within the constraints of a low input marginalised rural setting (Njoka-Njiru, Njarui, Abdulrazak, & Mureithi, 2006; Silburn, Robinson, & Freebairn, 2007). Grasses reduce evaporation and increase infiltration due to leaf litter and continuous soil cover, and reduce deep drainage and leaching below the deep and dense rooting zone. Grasses reduce runoff and soil erosion by maintaining higher ground cover and improve the water holding capacity of sandy soils over time through the build-up of soil organic carbon (Silburn et al., 2007). Pasture systems also provide greater yield stability and resilience, especially through droughts due to accessing deep soil water (SW) reserves (Silburn et al., 2007). They can provide an essential fodder; construction material and fuel; contribute to biodiversity and ecosystem services and can be traded as a commodity (Silburn et al., 2007; Snyman, 1999).

The disadvantage of pasture is that it is not a conventional cash or food crop and its rates of soil organic carbon improvement are slow, only adding 0.1-0.001 % organic carbon per year (Silburn et al., 2007). Furthermore, there are social challenges in mobilising communities to cultivate pasture as a crop as it is seen as a communal commodity and thus has never been embraced as a crop per se (Mureithi, Verdoodt, Njoka, Gachene, & Ranst, 2015). But intercropping drought tolerant food legumes such as cowpea *(Vigna unguiculata)* could integrate the pastoral advantages into conventional agriculture providing economic compensation in the form of a cash or food crop over the long periods of rehabilitation. Legumes which have long been a popular intercrop with grasses (Schultze-Kraft et al., 2018) as nitrogen fixed by legumes facilitates growth and thus soil organic matter accumulation which improves the water holding capacity. It would also alleviate potential soil fertility constraints and draw down within a marginalised low input system. This would indirectly improve the quality and economic viability of the pasture (Descheemaeker, Amede, & Haileslassie, 2009; Kabirizi, Ziiwa, Mugerwa, Ndikumana, & Nanyennya, 2013; Silburn et al., 2007; Yaacob & Blair, 1981). Cowpea has the further advantage of having highly nutritious edible leaves and beans, giving the options of leafy vegetable or protein from the bean (Heuzé et al., 2015).

The alternative conservation relay intercropping system where two or more food crops are grown simultaneously within pasture for part of their growth cycle has been termed ‘pasture cropping’ (PaCr), ‘companion cropping, or live mulch’ (to be referred to as PaCr throughout this manuscript) and was popularised in Australia (Seis, 2006). In Australia, PaCr is practiced in winter rainfall areas by sowing winter cereals such as wheat (*Triticum spp.*) directly into summer-growing native sub-tropical pastures (C4) to optimise their complementary growth phases and reduce direct competition (Millar & Badgery, 2009).

Figure 1-2 Colin Seis showing recently sewn wheat directly into pasture (Photo: Author).

The claimed advantages of PaCr include: greater profit and yield from combining grazing and cropping production, sustaining livestock numbers while cropping, increased ground cover, improved WUE through complete use of SW reserves, improved nutrient cycling, improved soil structure, greater management flexibility and reduced risk of cropping system failure when facing variable weather conditions (Bruce et al., 2005; Finlayson et al., 2012; Hacker, Robertson, Price, & Bowman, 2009; Lawes, Ward, & Ferris, 2014; Millar & Badgery, 2009; Seis, 2006). Apart from the benefits that the pasture element in PaCr could bring to a SSA context, there are other major potential advantages, such as possibly eliminating huge labour requirements for weeding and reducing the cost of manual (e.g. hand hoe) land preparation that is a crippling aspect of subsistence farming. This could save an estimated 550 hours/ha/season of labour input (Umar et al., 2012). This time saved could be used to increase the land area planted, if available, thus increasing yields.

The challenge of adapting PaCr to the SSA context is that it loses its relay benefits as it will have to be practiced in summer due to the summer rainfall, which results in both the pasture and the annual crop having an overlapping growth cycle which makes competition for water a potential limiting factor. No research has been done to quantify this based on water availability to either crop under summer based PaCr in SSA. This research provides a field trial through to model scale introductory assessment of the soil and water dynamics in PaCr and the implications thereof in yield, water use efficiency and competition for water, ultimately assessing the potential of PaCr in the context of crop water use within a SSA scenario.

2. Can Intercropping Leguminous Food Crops into Perennial Pasture Improve Water Use Efficiency, Risk Profile and Sustainability of Degraded Dryland Systems?

R N Orford[1], M van der Laan[2], J G Annandale[2], F Asch[1].

[1] The Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg-Institute), University of Hohenheim: Crop Water Stress Management in the Tropics and Subtropics, Hohenheim University. Garbenstr. 13, 70599 Stuttgart, Germany,

[2] The institute of Plant Production and Agroecology in the Tropics and Subtropics, Department of Plant and Soil Sciences, University of Pretoria, Private Bag X20 Hatfield, Pretoria 0028.

2.1 Introduction

The decline in subsistence farmer productivity in Sub-Saharan Africa (SSA) is associated with a decline in water use efficiency (WUE). Rainfed agriculture is practiced on approximately 95% of SSA agricultural land and thus predominantly rural agriculture populations rely almost exclusively on rainfed food production. Paradoxically approximately 70-85% of the rainfall is lost unproductively (Conway & Toenniessen, 1999; Johan Rockström, Barron, & Fox, 2002; Winterbottom et al., 2013).

Intercropping, where two crops are planted in one field in one season has many WUE advantages as extensively described in literature (Morris & Garrity, 1993b; Natarajan & Willey, 1986; Willey, 1990), however in most cases intercropping annual crops still results in significant water loss early in the season due to poor root and shoot development as the crops grow. Established perennial grasses (pasture) have a deep root system accessing deep soil water (SW) reserves and limits deep drainage and leaching. Above ground, there is reduced evaporation and increased infiltration due to leaf litter and continuous soil cover (Silburn et al., 2007; Snyman, 1994). Pasture reduces runoff and soil erosion from the beginning of the season by maintaining higher ground cover and improving the water holding capacity of sandy soils over time through the build-up of soil organic carbon (Silburn, Robinson et al., 2007). All these WUE aspects enable pasture systems to provide greater yield stability and resilience, especially through droughts and floods (Mureithi et al., 2015).

The interesting and key consideration is the interplay between WUE benefits of pasture in pasture cropping (PaCr) and how that influences the mechanisms of competition in a PaCr system. There have been cases where high density intercropping, such as PaCr, has failed in very dry conditions which would suggest that competition outweighed facilitation (Lightfoot & Tayler, 1987; Rees, 1986b). These mechanisms are poorly understood and competition is assumed to outweigh the WUE benefits and thus is a major limiting factor to its presumed success in high density systems in semi-arid summer conditions.

2.1.1 Literature Review

When considering yields of PaCr there are numerous anecdotal figures referring to crop yields from pasture cropping remaining about the same when compared to conventional cropping with 20-year oat yields averaging 2.5 ton/ha and examples of grain yields being above average (Christine Jones, 1999; White, 2012). Crops in most trials include winter crops such as wheat, oats or lupins.

However, field trials also have demonstrated lower than average oat yields of 0.7 tons/ha (Barrett-Lennard, Dolling, & Ferris, 2010). Lodge and McCormick (2006) did a 100 year simulation with the SGS Pasture Model for the winter rainfall region of northern New South Wales and concluded that PaCr would be a high risk cropping system due to insufficient stored soil water to initiate crop growth, suggesting a required 258 mm of rain to achieve a modest three ton/ha DM yield for wheat. Millar and Badgery (2009) found that in terms of DM, pasture out-yielded PaCr in one year and showed no significance in the second year. Lawes et al. (2014) did find some success in Western Australia when a "well-adapted annual is teamed with a summer-active C4 pasture that can be suppressed with herbicide in winter and remains dormant through the winter growing season". Colin Seis also cautions "that crop yields are usually lower than with conventional, industrial agriculture in the beginning". He says this is, "more than offset by the ability to produce two (or three) products from the same bit of land, plus all the fertility that is being built up in the soil "(White, 2012). A simple economic analysis of pasture cropping in the United States using winter wheat showed that overall net return was 202 US$/ha versus 118 US$/ha for conventional cropping. So in summary, the crop yields are less than conventional crop yields and pasture yields, but the overall return when including the pasture component and multiple crop offtakes can be better than conventional cropping (Glover, Duggan, & Jackson, 2010).

When looking specifically at water use, Ward *et al* (2014) concluded that WUE was lower for grain. This was offset by pasture production, thus WUE for biomass production in total was greater for the PaCr plots than for either the pasture or crop monocultures. They found that deep drainage on sandy soils was eliminated and that competition in the warmer season was offset by the complementarity offered by the deep roots of the pasture. Bruce *et al.* (2005) observed that the increase in total biomass under PaCr caused a reduction in SW content. The higher transpiration due to the higher biomass also tended to induce stress at an earlier stage relative to the monocrop, reinforcing the importance of competition for water.

When broadening the scope, there is again limited literature on legume-grass forage trials which primarily focus on nitrogen dynamics and forage quality (Baba *et al.*, 2011; Sengul, 2003; Ullah, 2010).

Johnston *et al* (2002) considered newly planted *Trifolium subterraneum* and *E. curvula*, concluding that *E. curvula* was more tolerant of water stress but showed poor competitive ability, whilst *Trifolium subterraneum* showed better competitive responses but wilted under drought stress. Liu Guobin *et al* (1992) found similar responses with established pasture with *Phalaris aquatica* showing higher tolerance to water stress versus *Trifolium repen*s, but *T. repens* showing better growth rates with available SW.

To compensate for limited literature on PaCr, let alone competition within PaCr, the fundamentals of below ground competition for water in intercrops using parameters of PaCr will be considered here. The competition that will be focused on is below ground competition as it is a bigger determinant of a competitive outcome in more arid climates (Casper & Jackson, 1997) which is where the focus of this research lies. When applying Goldberg's (1996) definitions (see See Figure 2-1) specifically to water, it is the effect plants have on an intermediary resource, such as water in this case, which is notable and the response of plants to a change in the availability of that water resource. This happens concomitantly to the effects of the environment on the availability of the water resource.

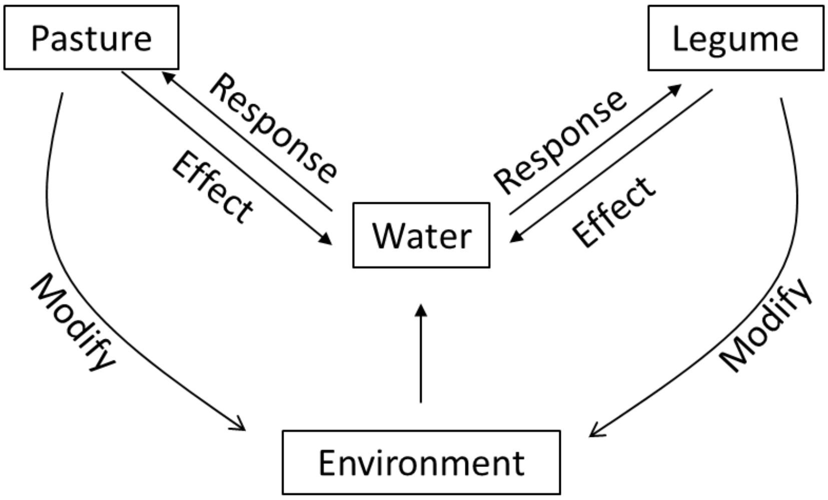


Figure 2-1 Plant competition as characterised by (Goldberg, 1996) with modifications by author. In this scheme plants must have an effect on the abundance of water and other plants must respond to the change. Crops also modify the cropping environment.

Briefly, the water uptake and resulting mechanisms of competition include (1) root interception of water whereby roots physically grow into soil with available water or (2) mass flow of water through the soil profile driven mainly by transpiration. Interception only represents <10% of the water uptake and thus is the least important. Furthermore, we assume the established nature of pasture roots will have an even smaller interception component relative to the cowpea new roots growing into an established pasture root volume. If we consider the traits related to belowground competition, pasture has the initial advantage that it has an extensive established root volume. Cowpea, on the other hand, has no established root zone at planting and will have to develop a specific critical volume of roots until it can compete. This, however, comes with a trade-off between the ability to explore large soil volumes like pasture can and that to exploit resource-rich patches as the roots grow like cowpea can. The plasticity of cowpea to, for example, morphologically proliferate roots in response to patches of soil water or with cowpea being isohydric (Jones, 1998) to physiologically have very tight stomatal control thus maintaining leaf turgor, may give cowpea an increased competitive ability. Lastly these interactions will all depend on the level of overlapping root volumes that are actively taking up water through transpiration. This is related to the degree of root partitioning due to different root depths and the coincidental timing of water uptake in an overlapping active root zone (Casper & Jackson, 1997). Therefore, it can be assumed that the primary uptake and thus mechanism of competition is mass flow of water driven by transpiration.

All this can be defined according to Vandermeer and Schultz (1990) with two principles. The "competitive production principle" considers differences in water use in time, space and physiology as discussed. This means that two different crops will not compete in the same way for a shared water resource which reduces the competitive severity relative to identical crops competing in an identical way for the same water resource resulting in direct and thus more severe competition. In the "facilitative production principle" plants modify the cropping environment; thus, growth is facilitated in one way or another for one or both crops. An example would be that mulch deposited by pasture will reduce evaporation and thus provide a greater availability of soil water to both cowpea and pasture. There are numerous other ways that the microclimate can be influenced which are beyond the scope of this assessment.

With this in mind the first objective of the field trial was to (i) assess the yield performance of PaCr over two consecutive seasons under summer rainfall conditions using cowpea *(Vigna unguiculata)* and an established Weeping Love Grass (*Eragrostis curvula*) pasture. Because water is most often the limiting resource in SSA dryland systems, the second objective (ii) was to specifically assess if there was a difference in soil water availability and thus an increase in WUE relative to the monocrop and to (iii) assess the competitive ability of either plant under pasture induced high-density conditions.

The hypothesis is that increased infiltration and reduced evaporation facilitated by the pasture in the PaCr system will outweigh the water demand of the higher plant density to the extent that there is a seasonal SW advantage which will allow PaCr to provide a total dry matter (DM) yield advantage compared to the equivalent monocrop system, ultimately suggesting that facilitation will outweigh competition in the PaCr system.

2.2 Methods and Materials

2.2.1 Study Site

A rain fed field trial was conducted at the Hatfield Experimental Farm of the University Of Pretoria, South Africa (25.74° S, 28.23° E, altitude 1339) during the 2013-2014 and 2014-2015 summer growing seasons. The average rainfall is 732mm a season.

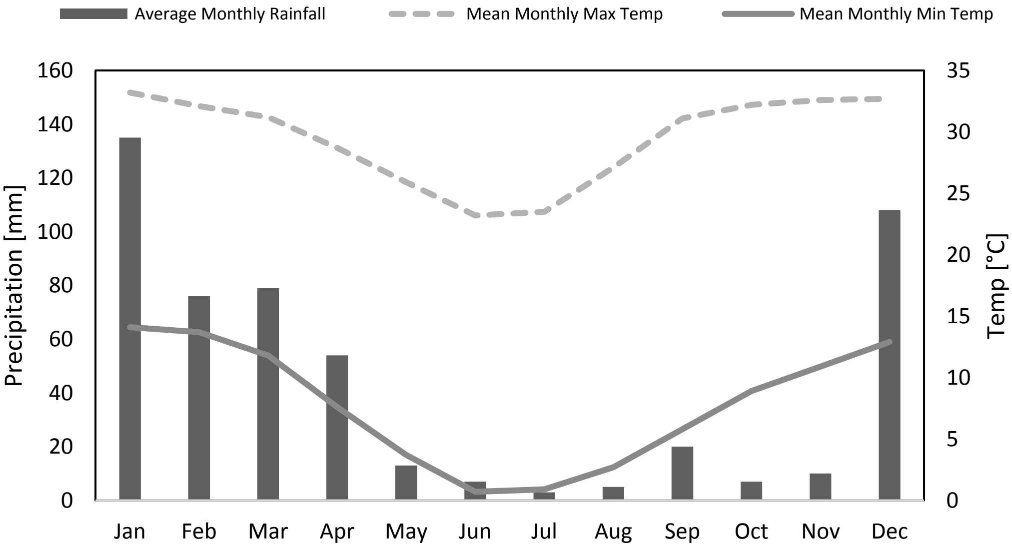


Figure 2-2 Average precipitation, minimum and maximum temperatures at the University Of Pretoria from 1961-1990, South Africa (25.74° S, 28.23° E, altitude 1000m).

A Delta T portable weather station was installed between the two fields. Rainfall, temperature, humidity and radiation was measured every 20 minutes. Season one (20-12-2013 to 10-04-2014) was a high rainfall growing season with 685 mm of rain falling over the trial period with an aridity index of one thus classified as sub-humid. This was followed by drought in season two (14-01-2015 to 16-04-2015) wherein only 190 mm of rain fell over the growing season. An additional 95 mm of lifesaving irrigation was added, distributed over 13 events in the first 35 days after planting (DAP). This was to avoid severe water stress induced wilting, bringing the full season two water input to 274 and 260 mm for the PaCr and monocrop section respectively. The aridity index for season two was 0.5 and thus is borderline between semi-arid and dry sub-humid. Differences in amounts of irrigation are attributed to different sprinkler application methods which incurred some divergence. Differences in rainfall can be seen in figure 2-3. Runoff was assumed as negligible due the fields being in a depression and on relatively level land.

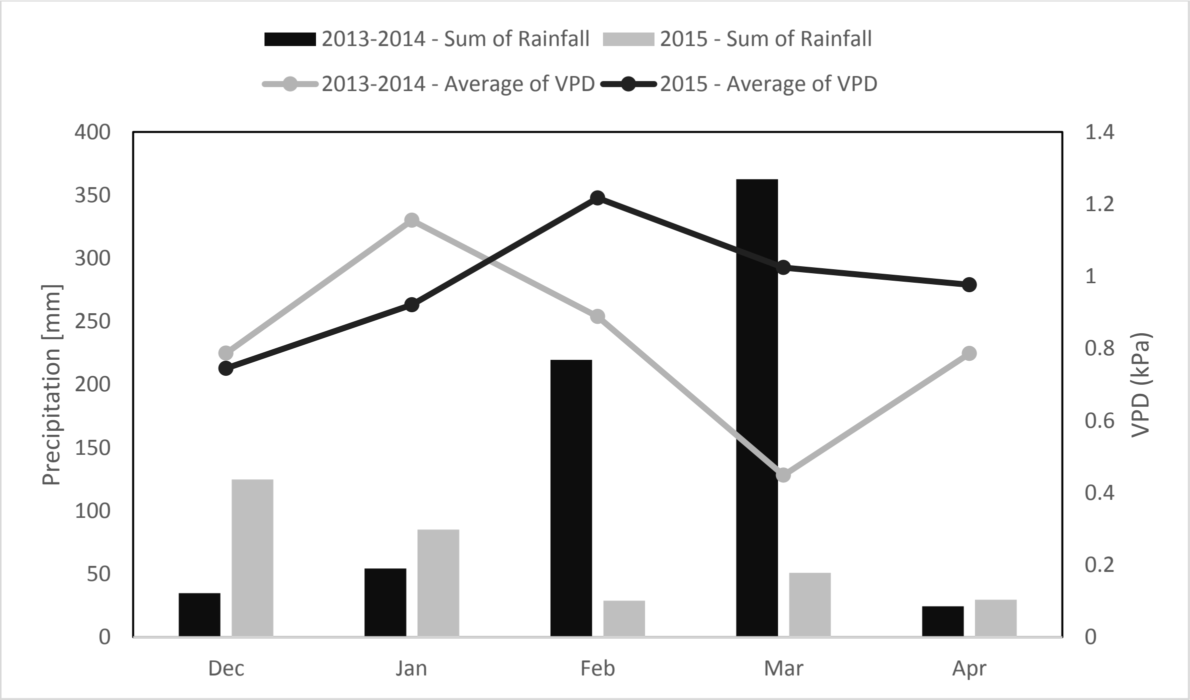


Figure 2-3 The sum of the monthly rainfall [mm] and average VPD [kPa] over the two different seasons.

Table 2-1 Average climatic parameters for the 2013-14 and 2015 season.

Parameters	2013-14	2015
Rainfall + Irrigation [mm]	675	260
Average Radiation [MJ m^{-2} d^{-1}]	19.38	21.85
Average Wind Speed [$m.s^{-1}$]	1.79	1.98
Average Eto [mm]	6.04	4.02
Average VPD [kPa]	0.77	1.04
Aridity Index	1	0.5

The soils are classified as oxidic red Hutton soils with a sandy, clay loam texture. Soil samples and bulk density were taken every 0.3 m to a depth of 1.2 m. Soil samples were analysed for texture and soil properties (see Table 2-2).

Table 2-2 Soil physical, texture and hydrological characteristics of the soils in the ploughed and pasture trial. Field Capacity (FC) and wilting point (WP) were all estimated based on the SPAW model (Saxton, 2005).

System	Depth [m]	Sand [%]	Clay [%]	Silt [%]	Bulk Density [g/cm3]	FC [% Vol]	WP [% Vol]
Ploughed	0-0.3	59	28	12	1.41	29	16
	0.3-0.6	43	30	27	1.58	35	24
	0.6-0.9	36	28	36	1.47	38	26
	0.9-1.2	40	31	29	1.40	36	24
	Average	45	29	26	1.47	34	23
Pasture	0-0.3	62	32	6	1.56	30.0	17.0
	0.3-0.6	41	35	24	1.47	36.0	24.0
	0.6-0.9	43	30	28	1.59	35.4	23.6
	0.9-1.2	35	32	33	1.32	38.0	26.3
	Average	45	32	23	1.48	35	23

The rain fed trial consisted of three treatments including a cowpea monocrop (CM), established pasture (PM), and an additive pasture cropping (PaCr) setup of cowpea directly seeded into pasture. All three treatments were prepared in a randomised complete block design with three repetition plots per treatment.

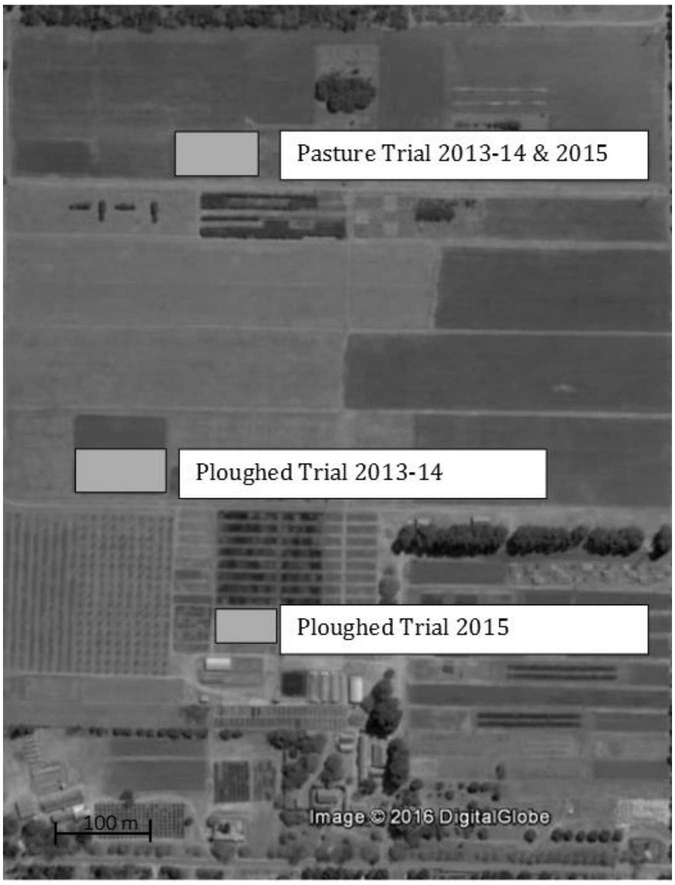


Figure 2-4 Map of the Hatfield Experimental Station trial site showing the layout of the fields over the trial period (Google Maps, 2016).

2.2.2 2013-14

2.2.2.1 Monocrop Treatment

The monocrop trial was located on a previously ploughed field. The monocropping treatment was prepared by ploughing a 100 m^2 plot twice to a depth of 0.2 m. The second tillage event was to remove weed establishment. Cowpea seeds (Var. Agrinawa (indeterminate)) were inoculated with rhizobia and manually planted on 20 December, 2013 at a depth of 3-5cm deep. The row spacing for cowpea was in line with semi-arid dryland practice of 0.8 m between rows and 0.4 m within rows bringing the planting density of cowpea to 32150 plants ha^{-1} (Lightfoot and Tayler, 1987). Granular fertilizer was split in half and applied in two stages (at establishment and at 30 DAP) totalling 100 kg N ha^{-1}, 50 kg P ha^{-1}, and 100 kg K ha^{-1}. Hand weeding was performed on the ploughed trial on four occasions over the season.

2.2.2.2 Pasture Treatments

PM and PaCr were on a nearby established pasture that had been harvested for hay in previous years. The established pasture (PM) consisted of 85% of the indigenous Weeping Love Grass (*Eragrostis curvula*), but had other sporadic species including *Digitaria eriantha, Hyparrhenia hirta, Panicum natalense, Panicum maximum, Urochloa mosambicensis* and *Sporobolus africanus*. The standard pasture trial was left untilled and mowed to a height of 0.05 m on the 9 December, 2013. The yield of the mowed pasture was recorded and denoted as pre-planting pasture (PPP) throughout the dissertation. It should be noted that the PPP was unfertilised. As pasture was established, the natural tuft density was approx. 333 000 plants ha^{-1}. After mowing, cowpea seeds were planted on 20 December 2013 into the established a 100 m^2 plot allotted to the PaCr treatment within the established pasture in the exact same way as the monocrop trial, with the exception of being planted into shallow (five cm) ripped rows within the pasture to minimise disturbance. The pasture plots received the same fertiliser amounts as the cowpea monocrop trial. Once the trial had been planted and established, nets were pulled over all the fields to protect the cowpea seed from birds. Nets were removed at 20 DAP.

For soil water measurements, three TRIME-PICO IPH/T3 ™ access tubes per treatment were installed as per the supplier recommended auger method to a depth of 0.6 m. Access tubes were left for the first 30 DAP for the soil around the tubes to settle.

Figure 2-5 Showing cowpea growing directly into pasture

2.2.3 2015

The variety of cowpea planted in season one only achieved 5% flowering (thus defined as indeterminate), and thus the trial was compared in DM terms. In the season two the cowpea flowered as normal. For the second trial the experimental design was maintained. Due to the post-hoc realisation of the indeterminate nature and unavailability of the *Var. Agrinawa*, the cowpea variety planted was Glenda. Aquacheck™ capacitance probes (0.6 and 0.8 m probes) replaced the TRIME-PICO IPH/T3 ™ to gather SW measurements on a 20-minute basis thus gaining better SW data resolution. Probes were installed 20 days before planting to allow settlement in the soil. The capacitance probe measurements were from 0.1 m down to 0.6 m. The capacitance probes were calibrated to the soil water measurements after the trial was completed. The ploughed cowpea monocrop trial had to be moved to enable access to irrigation due to the pre-trial threat of drought, and plot size was reduced to 18 m^2. In the PaCr trial cowpea seeds were planted in rows with hoes rather than a mechanised shallow rip.

2.2.4 Sampling

After 30 DAP, non-destructive measurements were performed. The leaf area index (LAI) was measured on a bi-weekly basis (weather permitting) using a Decagon LP-80 ceptometer. In 2013-14 SW was measured on a weekly basis (weather permitting) with a TRIME-PICO IPH/T3 ™ hand held probe which was slid down the access tube to 10 cm, 30 cm and 60 cm. After the non-destructive measurements, three random cowpea plants per plot were cut at ground level. Sampled Cowpea samples were separated into leaves and stems. Fresh leaves were used to measure leaf area using an LI-3100C Area Meter. Leaves and stems were then dried to constant mass and weighed. Pasture samples were randomly sampled 0.05 m from the tuft base using a 0.09 m^2 randomly selected quadrant. The removed vegetative matter was dried to a constant mass. Leaf litter was also collected once during the trial using a 0.09 m quadrant, dried to constant mass and weighed. This was to establish a reference value for modelling parametrisation.

2.2.5 Analysis

2.2.5.1 Water use efficiency

Water use efficiency was calculated based on (Sinclair, Tanner, & Bennett, 1984).

$$\boldsymbol{WUE}\ [\boldsymbol{kg\ mm^{-1} ha^{-1}}] = \boldsymbol{DM}\ \left[\boldsymbol{kg\ ha^{-1}}\right] \div (\boldsymbol{P} + \boldsymbol{I} \pm \Delta\boldsymbol{SW}) \qquad \text{Eq. 1}$$

where P = precipitation, I = irrigation, ΔSW = change in soil water

2.2.5.2 Land equivalent ratio

Crops were harvested five times over the season for both trials. Total aboveground dry matter (DM) yields were expressed per unit area and then used to compute the land equivalent ratio (LER, see Eq. 2) which is based on Mead and Rao (1980).

$$\boldsymbol{LER_i} = \frac{\boldsymbol{Y_{ij}}}{\boldsymbol{Y_{ii}}} \qquad \text{Eq. 2}$$

LER_i represents the land equivalent ratio of crop *i*. Y_{ij} *and* Y_{ii} represent the yield of the crop *i* per area within the PaCr, and monocrop setup respectively. LER_{plot} can be calculated by summing the DM yield for n species in a plot (i.e. $LER_i + LER_j$).

$$\boldsymbol{LER_{plot}} = \sum_{i=1}^{n} \boldsymbol{LER} \qquad \text{Eq. 3}$$

An LER_{plot} of greater than one suggests that the individual crops within the intercropping system yielded more per unit area combined compared to their respective monocrop yields, which is also known as ‘over-yielding’. This is attributed to resource complementarity/facilitation (Anders *et al.*, 1994). An LER below one would suggest that competition has outweighed resource complementarity/facilitation within the intercropping system, thus yielding less per unit area when combined compared to their respective monocrop yields. An LER of one would thus represent a mixed cropping system where production is not limited by one or other crop.

2.2.5.3 Competition

To analyse and present all the components of competition between the crops simultaneously, Snaydon and Satorre (1989) developed a bivariate diagram approach. The bivariate diagram can simultaneously present competitive indices such as competitive ability (Cb), competitive severity (Cs) and resource complementarity (Rc). On the diagram seen in

figure 2-6, are plotted points based on the expected yields and observed yields of either crop. These expected yields (Y_{ij} or Y_{ji} on the x and y axis) are calculated as follows:

$$\boldsymbol{Y_{ij\,expected}} = \boldsymbol{P_{ij\,expected}} \times \boldsymbol{Y_{ii}}$$

$$\boldsymbol{Y_{ji\,expected}} = \boldsymbol{P_{ji\,expected}} \times \boldsymbol{Y_{jj}} \qquad \text{Eq. 4}$$

Where $P_{ij\ expected}$ and $P_{ji\ expected}$ represent the expected proportional representation of either crop *i* and *j* within PaCr under the normalising assumption of equal competitive ability. It is important to note that the expected proportion is based on the on the “yield of each component in monoculture, and their sown proportion". Y_{ii} and Y_{jj} are the observed yields per unit area of their components in a monoculture. The expected proportions of either crop from a mixture ($P_{ij\ expected}$ or $P_{ji\ expected}$) are calculated based on Eq. 5.

$$\boldsymbol{P_{ij\ expected}} = \frac{\boldsymbol{P_{ij\ sown}} \times \boldsymbol{Y_{ii}}}{(\boldsymbol{P_{ij\ sown}} \times \boldsymbol{Y_{ii}}) + (\boldsymbol{P_{ji\ sown}} \times \boldsymbol{Y_{jj}})} \qquad \text{Eq. 5}$$

$P_{ij\ sown}$ represents the sown proportion of either crop in a mixture. The sown proportions were calculated based on the already established tuft density of *E. curvula* at 33 plants m^{-2} while cowpea's sowing density was at 3.125 plants m^{-2}.

The shifts of points $Y_{ij\ expected}$ and $Y_{ji\ expected}$ to the $Y_{ij\ observed}$ and $Y_{ji\ observed}$ on the bivariate diagram represents Cb, Cs and Rc.

The competitive ability (Cb) which is described by Wilson (1988) and incorporated into the bivariate diagram by Snaydon and Satorre (1989), is expressed as the shift of the expected yield to the observed yield in the north west-south east (NW-SE) axis as seen in

figure 2-6. This shift changes the hypothetical proportional cropping mixture, as seen by the shift from a 25% to a 50% representation of crop *i* as seen in

figure 2-6. The Cb can be directly quantified off the bivariate diagram as the NW-SE diagonal distance or numerically calculated by taking the difference between the logit of the actual proportions and the logit of the expected proportions.

$$\boldsymbol{C_b\ (P\ logit)_i} = \boldsymbol{ln}\ \left(\frac{\boldsymbol{P_{ij\ observed}}}{\boldsymbol{1-P_{ij\ observed}}}\right) - \boldsymbol{ln}\ \left(\frac{\boldsymbol{P_{ij\ expected}}}{\boldsymbol{1-P_{ij\ expected}}}\right) \qquad \text{Eq. 6}$$

The relative competitive severity (Cs) is defined, in this case, as the difference between the yield reductions due to intra-species competition (monocrop) versus inter-species competition in PaCr. Therefore, the severity is simply calculated as the ratio of the log transformed Y_{ii} to Y_{ij}.

$$\boldsymbol{Cs = log_{10}\left(\frac{Y_{ii}}{Y_{ij}}\right)} \qquad \text{Eq. 7}$$

This is the logarithm of the inverse of LER (see above). The severity of competition experienced by component *i* is measured along the –y axis of the bivariate diagram while that of component *j* is measured along the -X axis. It becomes apparent that the severity of competition experienced by each component is affected both by the degree of resource complementarity between components and by the relative competitive abilities of the components.

The LER value of one is expressed as a log induced curved line seen in figure 2-6. In the bivariate diagram the shift of expected to the observed yields beyond the curved LER line in the direction of the resource complementarity arrow (see arrow in figure 2-6) shows the degree of complementarity. A neutral complementarity is represented by an LER = 1 where both crops have equal competitive ability. If observed values lie beyond LER = 1, there is facilitation, while if the observed values fall behind this line, competition by one or both crops result in a reduced productivity of the system.

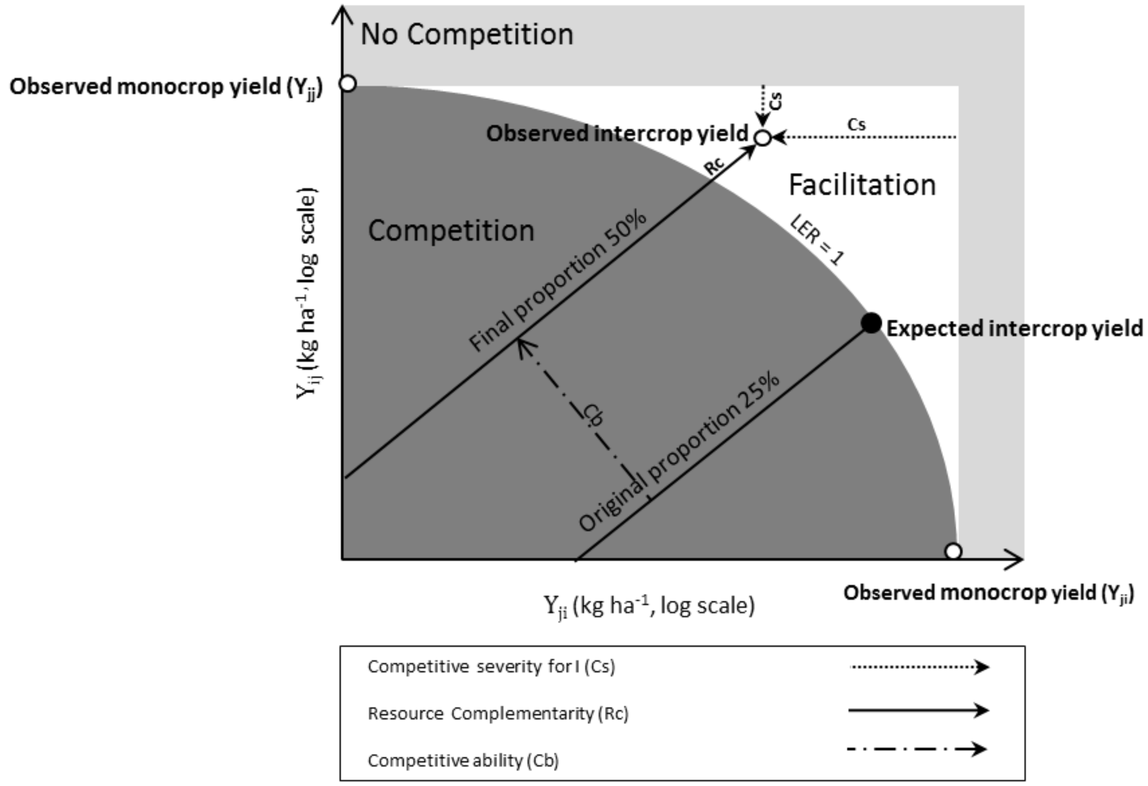


Figure 2-6 A hypothetical yield scenario of a log adjusted bivariate diagram adapted from Snaydon and Satorre (1989) with arrows to guide the interpretation of competition (competitive ability, resource complementarity and severity of competition). The curved line represents a LER=1 which also represents a balanced competitive outcome. The “no competition” area represents a crop mixture where either crop I and/or J experienced no competition and just facilitation, the area of “competition” represents both crops experience no facilitation and some level of competition and the “facilitation” area represents where crop I and/or J experience more facilitation than competition.

Wiley (1980) went further to describe the competitive ratio (Cr) between crops which is conveniently related to the LER_i and initial sowing/crop density proportions. The Cr value gives the degree of competition by indicating the probability that one crop is more competitive than the other (Willey and Rao, 1980).

$$\boldsymbol{Cr_i = \frac{Y_{ij}}{Y_{ii}} \div \frac{Y_{ji}}{Y_{jj}} \times \frac{P_{ij\,sown}}{P_{ji\,sown}}} \qquad \text{Eq. 8}$$

$P_{ij\ sown}$ represents the sown proportion of cowpea seeds per ha (31250 seeds per hectare which represents 9%) and $P_{ji\ sown}$ represents the number of pasture tufts per ha (333000 tufts per hectare which represents 91%).

2.2.6 *Statistics*

Excel was used to perform a basic t-Test. In the instance of competition the competitive ability (Logit) analysis was used to perform statistical differences (Snaydon R & Satorre E, 1989). Logit briefly is a statistical function which plots the probability values (0,1) to (-∞, +∞) (see Eq. 9).

$$\boldsymbol{logit(p) = log\,\frac{p}{1-p}} \qquad \text{Eq. 9}$$

2.3 Results

2.3.1 *Production*

There were no significant DM yield differences between all three treatments in the 2013-14 season. The cowpea monocrop yielded the lowest with 3.67 tons DM ha^{-1} while the pasture monocrop and PaCr produced 4.8- and 5.4-tons ha^{-1} respectively. The final DM ratio of cowpea to pasture was 32%:68%. The cowpea did not flower which resulted in no grain to assess. The cowpea DM yield penalty when planted with pasture was 72% while pasture showed a 33% yield penalty.

In 2015 the cowpea monocrop yielded the lowest again with 1.38 tons DM ha^{-1} while the pasture monocrop produced 2.87 tons DM ha^{-1} and PaCr yielded significantly ($P < 0.05$) higher tonnage than the monocrop treatments with 5.43 tons DM ha^{-1}. After 90 DAP this was higher than PaCr in 2013-14 season. The DM ratio of pasture to cowpea within the PaCr system was 93%:7%. The cowpea DM yield penalty when planted with pasture was 73% while pasture showed a 43% yield gain. There was no significant difference in the harvest index (HI) between the cowpea monocrop and cowpea in PaCr of 0.57 and 0.41. Some grain yield was lost to rodent damage in PaCr which reduced the HI and caused a high variability.

The inter-seasonal yield difference from a wetter to a drier year between 2013-2014 to 2015 was 62% drop for the cowpea monocrop, 63% drop for cowpea in PaCr, 41% drop for the pasture monocrop and counterintuitively 33% gain in pasture in PaCr. PaCr as a system showed a 0.3% gain.

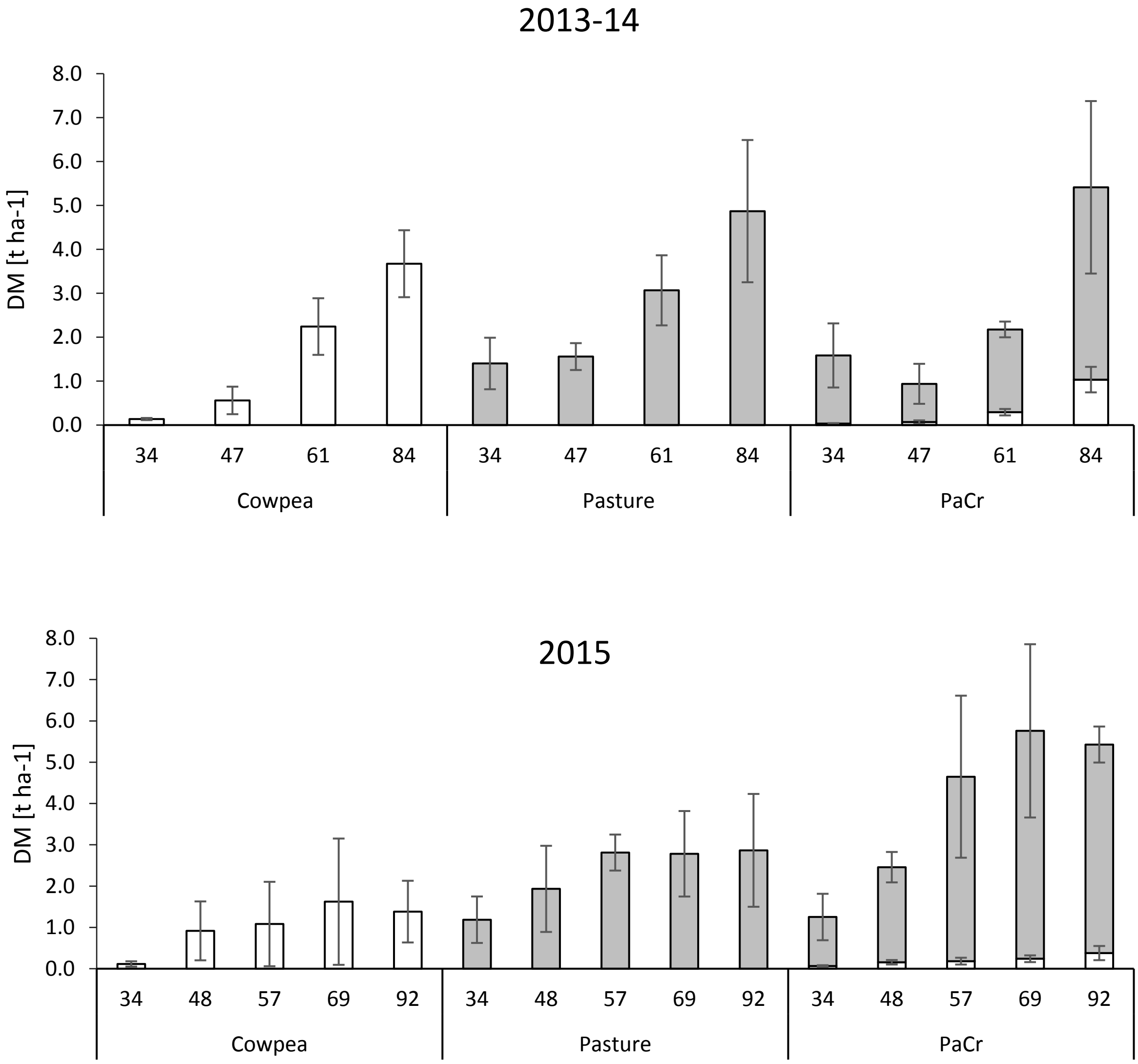


Figure 2-7 Stacked dry matter (DM) yield figures in tons per ha of the different system treatments after 90 DAP for 2013-14 and 2015. The error bars represent the standard deviation.

2.3.2 Morphology

Overall, there was a lower LAI in 2015 versus the 2013-14 season. Within the wetter 2013-14 season the treatments where cowpea was included had an insignificantly different LAI of 5.01 for PaCr and 5.48 for the cowpea monocrop, while the pasture monocrop was significantly ($p < 0.01$) lower with a LAI of 2.49. Conversely in the 2015 season, the LAI of treatments including pasture, showed a significantly higher ($p < 0.05$) LAI than the cowpea monocrop with PaCr and pasture getting 2.41 and 2.11 while the cowpea monocrop achieved 1.36. Just to note, in the pasture and PaCr trial there is a drop in LAI at 45 DAP which was attributed to a leaf curling phenomenon in *E. curvula* and thus reduced fractional interception. The specific leaf area (SLA) of the cowpea in all treatments showed no significant difference.

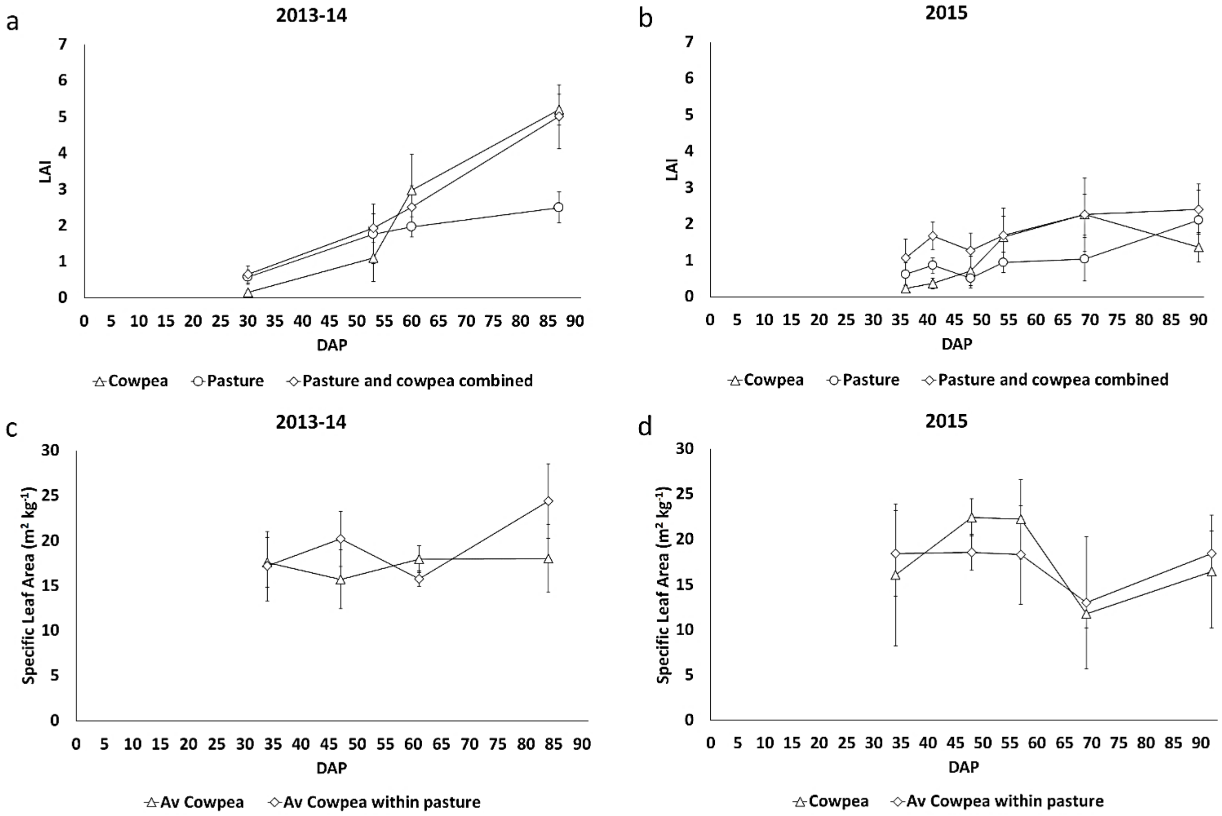


Figure 2-8 The leaf area index (LAI) (a,b) and specific leaf area (SLA) (c,d) of cowpea in a monocrop and cowpea within pasture.

2.3.3 *Water Use Efficiency*

The water use efficiency (WUE) was lower in the wetter 2013-14 season relative to the drier 2015 season. However, the cowpea monocrop showed a 27% lower WUE in the drier season. There were also no significant differences between treatments in 2013-14 and 2015 but the WUE advantages were more pronounced in 2015. In general, the pasture-based systems showed the highest WUE in both seasons with there being no significant differences between the pasture monocrop and PaCr in both seasons, PaCr being the most water use efficient in both cases. In 2015 the PaCr system was significantly higher ($P<0.001$) than the cowpea monocrop.

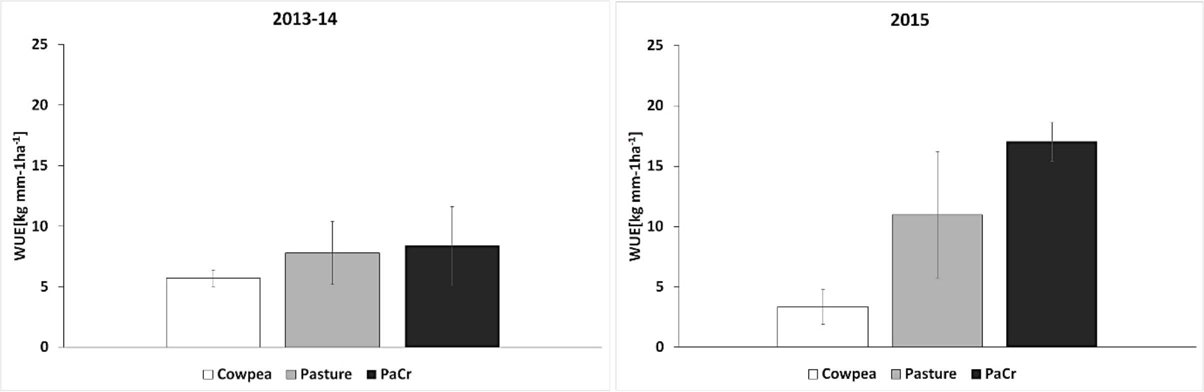


Figure 2-9 The water use efficiency (WUE) of the three different cropping systems in kg (Dry Matter) mm^{-1} ha^{-1}.

2.3.4 Soil Water

When considering the available Soil Water (SW) of the different cropping systems, the 2013-14 season had a higher seasonal rainfall and ET_o than 2015 as seen in figure 2-10.

The reduction in the SW deficit in 2013-14 following large rainfall events shows a subsequent pronounced deficit increase. In 2013-14 the cowpea monocrop and PaCr showed slightly greater deficits across the season and the SW deficit reduction after a large rainfall event was greater in pasture monocrop. In the 2015 season there was an overall steady decline in the SW deficit due to the limited rainfall. After 30 DAP after planting, the PaCr trial had a much smaller deficit of 13 mm versus pasture and the cowpea monocrop have a deficit of > 40 mm. The pasture and PaCr trial started with no deficit, whereas the cowpea plot started with a deficit of 15 mm at planting. Pasture had a very notable increase in deficit in the first 30 DAP, whereas PaCr had a much slower increase in deficit and hence at 30 DAP pasture and cowpea reaching similar deficit levels (see).

Cowpea monocrop and then PaCr showed a bigger deficit across the latter part of the season and the SW deficit reduction after a large rainfall event was much greater in pasture monocrop, followed by PaCr and with no increase in cowpea.

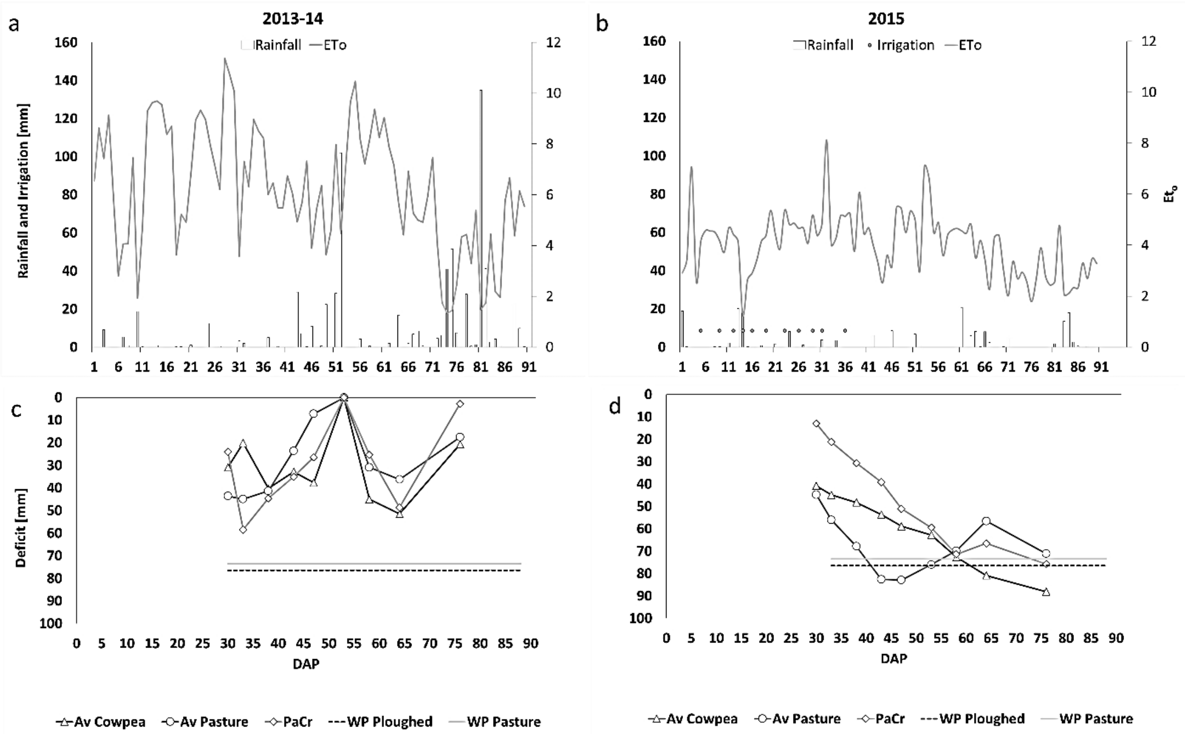


Figure 2-10 (a-b) Rainfall, irrigation and ETo for 2013-14 and 2015 (c-d) is soil water deficit with marked off wilting points (WP) within each treatment for 2013-14 and 2015 measured between 0.1 m and 0.6 m soil depth.

With the high-resolution SW measurements from planting in 2015 (see Figure 2-11 and Figure 2-12), the infiltration and transpiration rates of the three different treatments show that pasture and PaCr had >40 % more cumulative water transpired from the top 0.6 m of the soil profile relative to the cowpea monocrop. The decrease in SW, from all different depths and which is mainly attributed to transpiration, is very similar. What is noteworthy is that even though the SW levels were higher in the PaCr profile, the estimated amount of water transpired (ΔSW) by PaCr was higher than pasture and cowpea. When considering infiltration, which was estimated by an increase in SW at respective depths, pasture and PaCr had 49% and 107% times more infiltration in the top 0.6 m of the profile respectively than cowpea. Significant here is that only 5 % of the infiltration went below 0.3 m in the cowpea monocrop, whereas 14% and 15% infiltrated deeper than 0.3 m in the pasture and PaCr treatments. Therefore, there were greater and deeper infiltration in treatments with pasture. There was also more water available at the start and end of the 2015 season in the cowpea monocrop, whereas PaCr and then pasture had less initial and final SW, which means that there was more SW used from the 0.6 m soil profile where pasture was part of the cropping system.

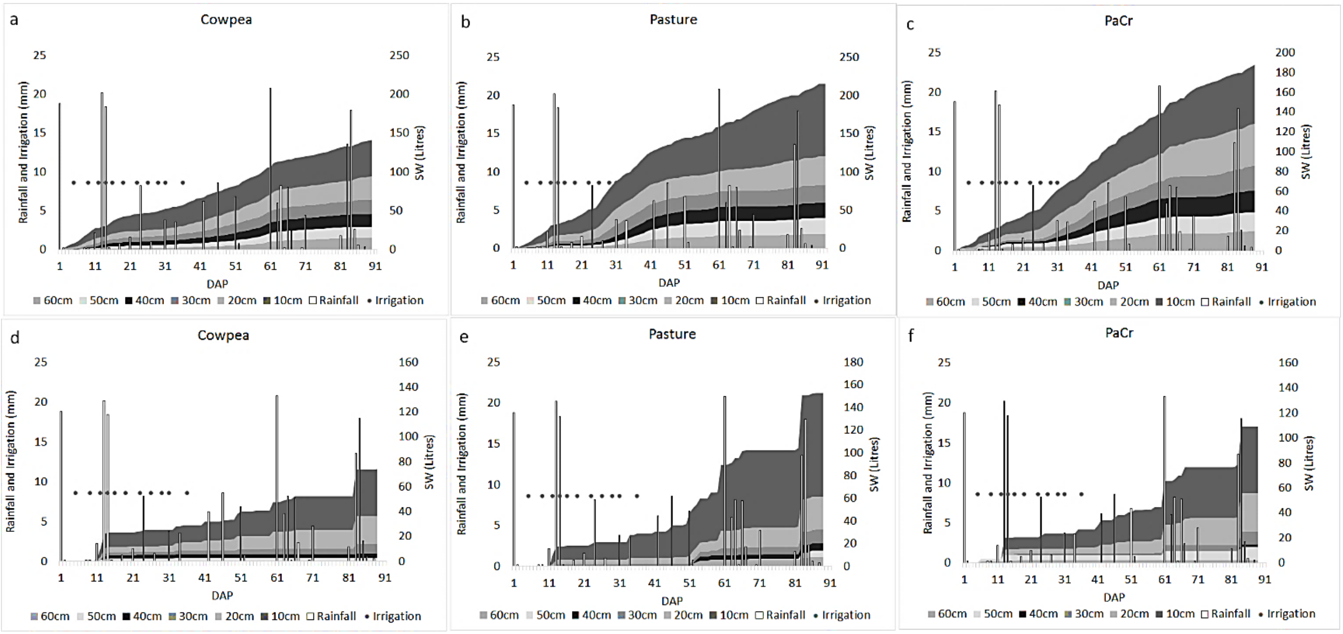


Figure 2-11 (a-c) Rainfall and irrigation with cumulative inferred transpiration for each depth. Transpiration considered for 0.1 m to 0.6 m depth of the profile. (d-f) Rainfall and irrigation and cumulative infiltration for each depth. Infiltration only considers the SW inputs between 0.1 and 0.6 m depth.

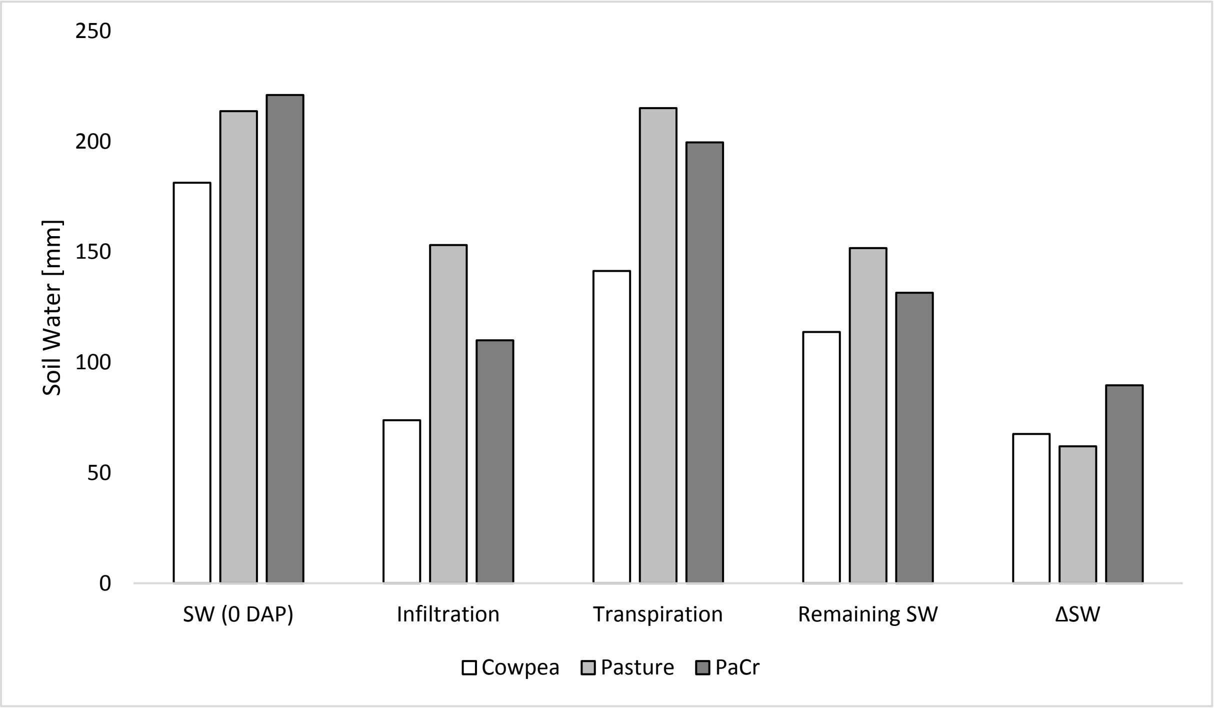


Figure 2-12 A breakdown of the water balance parameters for different treatments for the 2015 season.

2.3.5 Competition

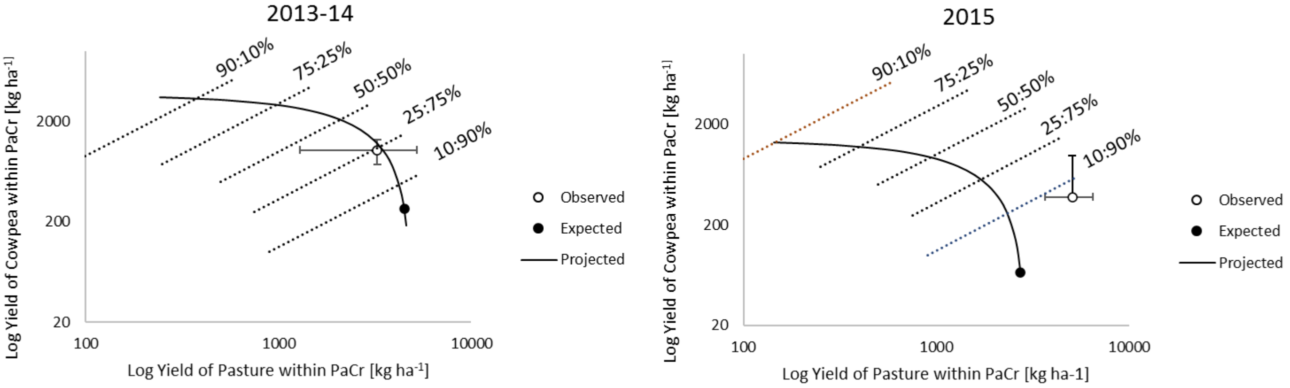


Figure 2-13 A natural logarithm transformed bivariate diagram based on Snaydon and Satorre (1989). The axes are the natural log yields in [kg's ha^{-1}]. The (•) represent the expected yield based on Snaydon and Satorre (1989). The open circles represent the observed yields (o). The solid curved lines represent the land equivalent ratio (LER) frontier = 1. The pasture crop = PaCr. The diagonal lines (……..) represent the proportional representation by DM weight of cowpea to pasture within PaCr as a %. Error bars represent standard deviation.

2.3.5.1 LER

The distance of the observed yields on the bivariate diagram beyond the LER=1 indicates that in 2013-2014 there is a statistically insignificant level of resource complementarity with an LER of 1.34. In 2015 the coordinates of the observed yield lie significantly beyond the LER of 1, with a value of 2.37, which shows significant resource complementarity (see Figure 2-13 and Table 2-3). This suggests a 4% and 102% land equivalent DM yield advantage, with the biggest advantage in a drier year. This larger shift is due to the gains of the pasture component in PaCr relative to the expected yield.

2.3.5.2 Competitive ability

The bivariate diagram shows that in 2013-2014, cowpea in PaCr had a positive proportional shift from the expected proportion of 7% to an observed proportion of 24 % which amounts to cowpea gaining 17% in its proportion while pasture losing equivalent 17%, thus expressing a stronger competitive ability. The results are rather different for the drier 2015 season where the cowpea only managed to increase its observed proportion from 5% to 7%, which is a total gain of 2% in proportion gain versus a 2% loss by pasture in its competitive ability. This clearly shows that cowpea had a more competitive ability in a wetter season relative to a drier one. *E. curvula* had correspondingly lower competitive ability relative to cowpea. Conversely to cowpea, *E. curvula* showed a greater tolerance to competition in the drier 2015 season. With respect to logit differences, there was no statistical significance (see Table 2-3).

2.3.5.3 Competitive Severity

When considering the severity of competition vertically and horizontally along the y and x axis, cowpea managed to gain 285% in 2013-14 whereas pasture showed a -28% left shift horizontally suggesting that the pasture experienced a very limited degree of competition in 2013-2014. In 2015 cowpea gained 470% more yield (upward shift along the y axis) relative to the expected for 2015. However, the seemingly large increase comes of a low expected cowpea yield. In pasture, there was an 85% shift to the right suggesting that there was significantly more facilitation than competition for the pasture gain in observed yield from the expected 2015 season. Therefore, the severity of competition was minimal to absent for *E. curvula* and was absent altogether for cowpea.

In Table 2-3 the competitive ratio summarises the results indicating that cowpea is 4.91 times more competitive in a wetter season and 2.54 times more competitive in a drier season whereas *E. curvula* is only half as competitive as cowpea, irrespective of season. Furthermore, the directional shifts from expected to observed yields of cowpea, seen in both bivariate diagrams, is very similar, suggesting that competitive dynamics are similar for cowpea regardless of water availability.

Table 2-3 Summary of the various competitive indices.

	Cowpea		**Pasture**	
	2014	**2015**	**2014**	**2015**
Competitive ability (Logit)	1.40	0.88	-1.40	-0.88
Competitive severity (% of monocrop)	14%	3%	-14%	-3%
Competitive Ratio (Cr)	4.91	2.02	0.48	0.79
LER_i	0.30	0.31	1.04	2.06
LER_{plot}	1.34	2.4		

2.4 Discussion

The primary objective of this research was to see if the PaCr cropping system would yield enough DM relative to a conventional cowpea or a pasture monocrop to justify PaCr as a potential sustainable sub-tropical farming system to relieve food insecurity in SSA over varying seasons. The secondary objective was to interpret the DM yield results between the two systems in relation to the differences in the corresponding SW results. The concluding objective was to interpret if SW differences were a significant driver of competition thus interpreting the DM yield outcome.

2.4.1 Production

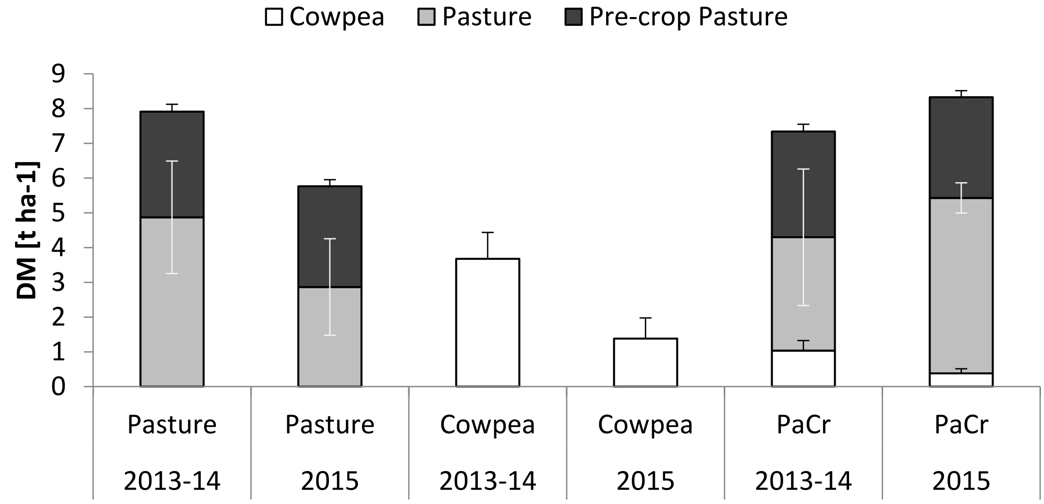
The DM yields of PaCr were 47% and 293% higher in both seasons compared to the conventional cowpea monocrop yield. When comparing PaCr yield to conventional pasture, there was a 11% less and 89% more DM yield in both seasons compared to the conventional pasture yield. The greater yield advantage in 2015 with the limited rainfall may suggest that PaCr used the stored soil water to supplement growth from 57 DAP, and hence an increased DM yield in a drier year which would be a time of greatest risk and food insecurity. PaCr and pasture SW levels were relatively similar at planting, however, there was a much slower rate of soil water reduction in PaCr versus pasture, which resulted in there being a 31 mm greater deficit in pasture versus PaCr. This may explain the unexpectedly high yields of the pasture component in PaCr. The mechanisms behind the slower rate of soil water reduction in PaCr cannot be explained by lower LAI therefore less transpiration, as in fact, the LAI was higher in PaCr. When comparing all SW depths, it was primarily the 0.1 m depth in PaCr that consistently retains about 10-15 mm more soil water. Another explanation, even with an equal 100 kg split nitrogen application, that there was a more persistent supply of nitrogen to the pasture in PaCr from nitrogen fixing cowpea nodules (Fukai & Trenbath, 1993).

When considering component crop performance within the PaCr mixture, cowpea had a 72% yield penalty in the wetter 2013-2014 and a 73% yield penalty in a drier 2015. When comparing similar high-density intercropping trials, the DM yield penalties for cowpea are high but comparable. Cowpea intercropped with sorghum suffered yield penalties of 78% and 42% relative to the monocrop (Lightfoot and Tayler, 1987; Rees, 1986). For the pasture component, there was an insignificant decline of 33% in the wetter 2013-14 year and unexpected 76% increase in yield in the pasture yield within PaCr in the dry year. This can be attributed to a persistence in soil water levels relative to the undisturbed pasture which was considered unusual. Sengul (2003) found an average 75% yield penalty of *Medicago sativa* L. planted with various grasses under dryland Mediterranean conditions and an average 17% yield drop for the various grass components. There was one case of a 4% yield increase.

If one considers the yield difference in terms of DM adding the yield of the pasture that was removed to prepare the PaCr trial for planting then PaCr looks rather more compelling (see Figure 2-14). It is estimated that cumulatively there was 100% more DM produced in 2013-14 PaCr versus the cowpea monocrop and 500% more DM produced in 2015. These stark differences take into account that the pasture in PaCr allows for DM to be yielded multiple times through the season, capitalising on wetter periods and thus spreading the risk. The multiple harvests idea of a perennial pasture is a significant contributor to the advantage of the PaCr system. It has been shown that *E. curvula* grazed every 4-8 weeks can double production in a season and improve quality relative to not being grazed (Cook *et al*., 2005. ; Masters and Britton, 1990).

The perennial nature of the pasture component of the PaCr system determines the resilience of such a system. This was demonstrated by 62% yield drop for the cowpea monocrop in lower rainfall in 2015 from the wetter 2013-2014 season whereas the PaCr and PaCr plus pre-planting pasture system actually increased by 26% and 18% from the wetter 2013-14 to 2015. This hypothetically implies much greater DM yield stability across varying weather conditions relative to the monocropping system. It also suggests that PaCr improves DM yield stability under extreme and varying climatic conditions which are becoming a reality in SSA (Beddington *et al*., 2012). This is in line with literature which proposes that the more species in a cropping system, the greater its yield stability and return on investment (Lightfoot et al., 1987; Mead et al., 1986).

When extrapolating with protein estimates from literature (FAO, INRA, CIRA, www.feedopedia.org), PaCr produced 69% more protein in 2013-2014 and 80% more in 2015 than the cowpea monocrop. Conversely, PaCr produced 206% more protein than pasture in 2013-2014 and a 108% more in 2015. With the pre-plant pasture included, the differences are again more compelling with 124% and 219% more protein yielded from the PaCr than cowpea alone and 141% and 278% more protein yielded from PaCr than P.



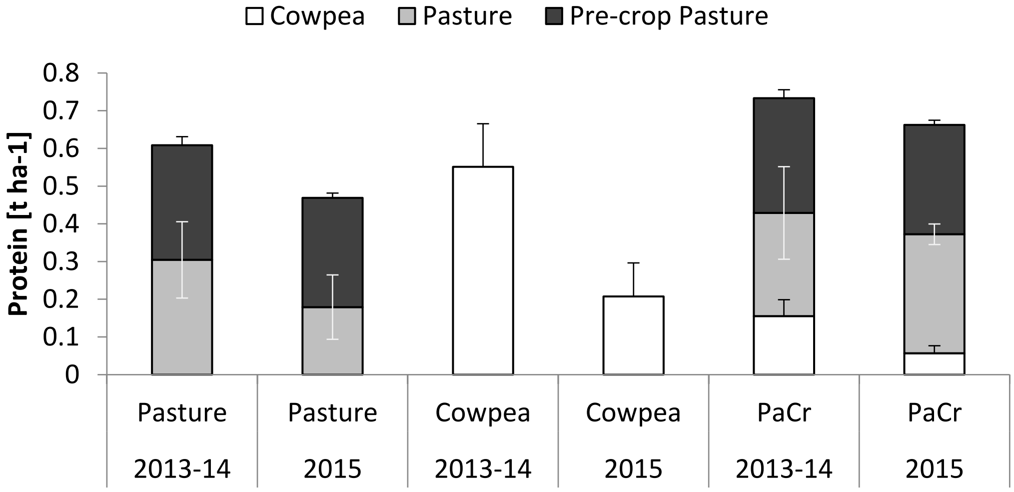


Figure 2-14 Top: Stacked DM yields with the pre-crop pasture included. Below: Estimated protein yields figures in tons per ha of the different system treatments after 90 DAP.

2.4.2 Soil water

The pasture element in PaCr was hypothesised to improve the availability of water and thus productivity for the cowpea in PaCr to such an extent that it would outweigh the competitiveness for water between both crops. The overall SW deficit results suggest no clear deficit differences or trends to clearly conclude that the PaCr deficit was bigger than the cowpea monocrop in inducing water-driven competition (see figure 2-10). In 2013-14 the greatest deficit was experienced by the cowpea monocrop, followed by PaCr and then pasture. This can be attributed to the corresponding order of higher to lower LAI thus inducing greater transpiration. In 2015, the drawdown of SW was greater in the pasture and PaCr trials and less so in the cowpea monocrop which can be attributed to the higher planting density and order of higher to lower LAI thus inducing greater transpiration. Based on measurements at depths between 0.1 m – 0.6 m, there was an approximately 49% and 107% higher cumulative infiltration for

PaCr and pasture monocrop respectively (please see) relative to the cowpea monocrop. This strongly suggests that the unploughed and relatively undisturbed pasture was conducive to improving the soil infiltration rate significantly. This corresponds to the literature (Silburn *et al*., 2007; Snyman, 1990).

Conversely the very high cropping density and higher leaf area of the PaCr system, increased the transpiration and uptake to such an extent that it reduced SW rapidly to lower levels than the monocrop during extended dry periods between 28 and 54 DAP. This is indicated by the steeper slope of the cumulative transpiration in a-c. In terms of losses between 0.1 m and 0.6 m depth, which we assume is primarily from transpiration, the PaCr and pasture transpired 41% and 52% more water, respectively, than the cowpea monocrop in 2015. This proposes that in drier conditions the PaCr system transpires more water from onset of the season through the already established deeper perennial roots which access SW reserves and thus yields more DM than a cowpea monocrop. This is in line with literature and yield results (Brye *et al*., 2000; Silburn et al., 2007; Snyman, 1997).

With the conventional assumption that pasture would induce higher transpiration and thus outcompete the cowpea added to PaCr the following evidence concludes otherwise. The inferred higher infiltration rate as deduced by increased SW values at different depths in the soil, was enough to compensate for the higher transpiration so that the deficit between PaCr and the cowpea monocrop was always similar. Therefore, the pasture induced benefits of improved infiltration negate the increased transpiration which usually would drive competition between cowpea and pasture in PaCr. As radiation is usually not a limiting factor in semi-arid sub-tropics between similarly tall crops (Holmgren, Scheffer, & Huston, 2009) and water has been shown to have similar deficits in both the monocrop and in PaCr, it suggest there are other factors such as soil nutrients playing a role in the yield penalty for cowpea in PaCr versus cowpea as a monocrop. In a maize-cowpea intercrop system, Wahua (1981) found that at 105 kg N/ha, the crops were in competition for N and that this occurred before anthesis or flowering (Ofori & Stern, 1987).

2.4.3 Water Use Efficiency

The increased productivity of PaCr versus the cowpea monocrop particularly in a dryer year is reflected in the 47% and 409% higher Water Use Efficiency (WUE) for 2013-14 and 2015 respectively (see Figure 2-9). Comparisons between the monocrop and PaCr in PaCr literature is limited due to different planting dates that are separated into winter/summer planting. Furthermore, there are variations in calculating WUE, planting densities and other exceptions. Nevertheless, Ward, Lawes & Ferris (2014) averaged WUE values of 6.5 to 12.2 kg mm^{-1} ha^{-1} for PaCr with *Hordeum vulgare* and *Lupinus angustifolius* under the winter rainfall in Mediterranean conditions of south-western Australia, but showed lower WUE values than the monocrop for all seasons. A similar intercropping trial such as Morris and Garrity

(1993a) show WUE when intercropping cowpea and pearl millet of 8-13 kg mm^{-1} ha^{-1} which was -8 to 55% higher than the respective sole crops.

Reasons for the increased WUE have been listed as increased capture of a large portion of ET as transpiration by intercrops (Van Duivenbooden, Pala, Studer, Bielders, & Beukes, 2000). This can be seen in . There is a greater efficiency of dominant species components which in this case would be the pasture. Masters and Britton (1990) also found that clipping *E. curvula* produced more fresh leaves which have more effective stomata, thus improving WUE twice over. Lastly there may have been an interception of more radiation by intercrop shown by the slightly higher SLA of the cowpea in the PaCr which is possible reason suggested by Sekhon *et al* (2010).

The significant yield advantage in the drier conditions is most probably due to the pasture element being less sensitive to the drier conditions (Johnston et al., 2002). As a C4 crop with deep dense roots accessing deeper SW reserves and adaptations such as leaf rolling and waxy cuticles, it is well evolved to cope with drier conditions. A single tuft of *E. curvula* has been observed to have 57% of the roots mainly in the top 0.25 m however found 11% of the root biomass between 0.75-1 m deep (Snyman, 2005). Some authors suggesting *E. curvula* accessing groundwater at a depth of 1.5 m (Snyman, 2005). This expansive root network makes *E. curvula* very effective at taking up water right through the profile. This includes the predominantly small rainfall events (<15 mm) from early on in the season to accessing deep SW as shallow SW is depleted (Johnston et al., 2002). In contrast, cowpea only had access to the SW relative to its root depth, which in this study only is estimated to have reached a maximum depth of 0.6 m at 40 DAP. Additionally, the established pasture utilises every rainfall event while reducing evaporation, whereas a planted annual monocrop such as cowpea loses a large proportion of the pre-planted rains to evaporation and drainage due to the undeveloped roots. The possibility of fixed nitrogen by cowpea may also have contributed to higher WUE.

2.4.4 Competition

When considering PaCr's competitive dynamics, the wetter season of 2013-14 offered limited resource complementarity. However, cowpea's competitive ability was at its highest while *E. curvula* was at its lowest in 2013-14, which implies that cowpea competed more severely than *E. curvula*. Therefore, there was a relatively equal trade-off between cowpea's gains and *E. curvula's* losses.

In 2015 these dynamics shifted with there being some significant resource complementarity. Cowpea's competitive ability was constrained to only 2%, which reduced its competitive severity against *E. curvula.* Furthermore *E. curvula* showed no signs of experiencing competition whatsoever, and over-yielded, resulting in an LER of 2.02. Natarajan and Willey (1986) showed similar results whereby the more abundant the SW resource the lower the resource complementarity. However, for drier conditions, Rees (1986a) showed that under severe stress the level of complementarity was lost. Therefore, it is rather unusual that at the combined PaCr planting density of 365 000 plants per ha, there was a strong degree of complementarity.

What was also unexpected, as one would anticipate according to traditional competition literature such as Black *et al* (1969), that a C3 crop like cowpea would be out competed when planted together with a C4 grass like *E. curvula* under water stressed sub-tropical conditions with high radiation. Furthermore, C4 crops such as *E. curvula* are better adapted to water stress and should hypothetically competitively dominate a C3 crop such as cowpea in a dry season like 2015. Black et al, (1969) presented a hypothesis to better understand weed-crop competition, classifying cowpea as an inefficient crop and hypothetically would be a poor competitor, with particular reference to the high-water requirements. But this was not the case in this trial. When considering *E. curvula* as a competitor it was shown in an experiment by Johnston *et al* (2002) that when *Trifolium subterraneum* was grown in mixed crop with *E. curvula*, it was not a strong competitor, particularly when *T. subterraneum* was planted early in spring before *E. curvula* had its first growth flush. But in the referenced experiment, *E. curvula* was newly established in a pot experiment, and in this trial the *E. curvula* was well established in an older pasture. Nevertheless, Johnston *et al* (2002) results are in agreement with the PaCr results showing that *E. curvula* did not significantly dominate cowpea.

To determine the mechanisms that affected the way that cowpea competed with *E. curvula*, it is important to distinguish whether the competition was above or below-ground. Firstly, the pasture had been mown before planting which would have reduced its competitive ability above and below ground. But in general competition was assumed to be predominantly below ground. Literature also confirms that below-ground competition is the dominant factor in the sub-tropics and tropics, particularly where water, and not radiation, is the limiting resource (Holmgren et al., 1997; Wilson, 1988). Radiation was also equally abundant in both seasons so it can be assumed that soil water, which varied drastically between seasons, played a more significant role than radiation in cowpea's competitive ability.

In the 2013-14 season, the abundance of SW from higher rainfall resulted in below-ground competition not being as much of a limiting factor to cowpea's competitive ability. However, in 2015, once cowpea had been established with supplementary irrigation, cowpea's competitive ability was constrained due to the limited SW availability in the top 0.6 m. What is surprising is that cowpea still managed to retain some of its competitive ability under such limited SW conditions. Johnston *et al* (2002) explained that when *T. subterraneum* was planted with *E. curvula, T. subterraneum* was completely dependent on available SW in the top 0.6 m of the soil profile, whilst *E. curvula* was shown to dry out the soil profile to a depth of 1.2 m. These results correspond to the SW dynamics in the PaCr trial. When the SW in the top 0.6 m was depleted, and because cowpea is isohydric, cowpea would have closed its stomata and reduced assimilation, whereas *E. curvula* would have employed leaf rolling and leaf waxing to control water loss whilst accessing deeper SW reserves and continuing to transpire under drought stress conditions. This could explain how *E. curvula* was largely unaffected by cowpea competition and could be described SW resource partitioning as described by Wiley (1990). Furthermore, cowpea did not often wilt under water stressed conditions, whilst in the Johnston *et al* (2002) trial, *Trifolium subterraneum* would wilt frequently. In PaCr trial, cowpea showed no signs of wilting, which can be attributed to cowpea being isohydric and thus having a very tight stomatal control thus maintaining leaf turgor. Cowpea also reduced the number of leaves relative to the monocrop, which reduced the transpiration surface area. A water stress coping mechanism such as this sacrifices the assimilation of CO_2 to maintain higher leaf water potential (Chaves et al., 2002). This explains the poor yields by cowpea in 2015.

Radiation did, however, seem to play some role in the competitive interactions of PaCr. Cowpea increased its SLA by 20% in 2013-2014 and 12% in the drier 2015 season. This seems reasonable as there was more shading initially by *E. curvula* in the wetter 2013-2014 seasons than in the drier 2015 season, where growth was so limited that shading was less of a factor. This response is well documented in the literature (Tsubo et al., 2001). Cowpea also had 84% and 106% higher leaf to stem ratio than the cowpea monocrop for the 2013-14 and 2015 season respectively, showing that cowpea partitioned more assimilates to leaves than stems. Thus, cowpea in PaCr adapted partly to the lower radiation conditions by apportioning more assimilates to produce relatively more and thinner leaves in a PaCr system than in the monocrop to improve radiation interception.

What is also interesting with regard to the competitive outcome of the PaCr is that according to the literature across ecological, agricultural, weed science and root competition, there are views on the influence of water stress on the competitive outcome of an intercropped or mixed system. The more traditional perspective known as the stress gradient hypothesis (SGH) put forward by Bertness and Callaway (1994), is that under water stressed conditions, neighbouring plants can improve soil conditions and microclimate through for example mulch or reduced wind speed respectively, which is said to play a role in the amelioration of neighbouring plant water availability and thus would influence the competitive dynamics between crops under water stress in a positive way. This differs for the results from intercropping literature, root competition literature and more current perspectives of the SGH which suggest that under levels of severe water stress competition for water increases to such an extent that competition outweighs facilitation resulting in a more negative relationship between facilitation and water stress. (Casper and Jackson, 1997; Lightfoot and Tayler, 1987; Michalet et al., 2014; Natarajan and Willey, 1986; Schenk, 2006). However, the outcome is dependent on factors such as plant life strategies, planting density and root architecture. This contradicts what is the case in this study, where PaCr performed exceptionally well under water stressed conditions of 2015, with an LER of 2.11, which according to Willey (1990) suggests facilitation.

It is also worth adding that if extra land is available, the estimated 550 hours/ha of labour time saved by PaCr due to eliminating the need for weeding and ploughing, allows more time to expand the cultivated area, thus increasing overall productivity of the cash crop and forage for a household (Umar et al., 2012).

2.5 Conclusion

From the results observed in the two seasons, there is compelling evidence to suggest that using PaCr to grow DM for forage and maybe for leafy vegetable material for human consumption is a compelling option. This is particularly the case in agropastoral systems where feed for cattle is so necessary. When protein is sought after a wetter year such as 2013-14, cowpea provides sufficient protein, but no more than the combined pasture and pre pasture. The DM matter advantages in the dry 2015 season showed very significant yield advantages which would indicate from the limited data set that PaCr is a significantly better DM yielding system than a cowpea monocrop. This is also very pronounced in terms of estimated protein. The SW differences were less pronounced which was anticipated and which is indicative if improved infiltration compensating for the significantly higher rates of transpiration, which proposes that a water deficit is not as much of a limitation in PaCr as was expected. From a competition perspective, cowpea was shown to be the primary competitor, gaining in yield above the expected proportion in both seasons. Pasture was not too affected by the cowpea, but did experience competition from cowpea in 2013-14 which was assumed to be related to radiation. The partitioned nature of pasture roots in PaCr and the competitive ability of cowpea enables PaCr to provide DM yields that exceed the monocrop equivalent with no negative SW implications.

2.6 References

Adiku, S. G. K., Carberry, P. S., Rose, C. W., McCown, R. L., & and Braddock, R. (1995). A maize (Zea mays)-cowpea (Vigna unguiculata) intercrop model. *Ecophysiology of Tropical Intercropping*, pp. 397–406.

Allen, R. G. (1998). FAO Irrigation and Drainage Paper Crop by. *Irrigation and Drainage*, *300*(56), 300.

Annandale, J. G., Benadé, N., Jovanovic, N. Z., & Du Sautoy, N. (1999). Facilitating irrigation scheduling by means of the soil water balance model. In *WRC Report No. 753/1/99*.

Annandale, J. G., Jovanovic, N. Z., Campbell, G. S., Du Sautoy, N., & Benadé, N. (2003). A two-dimensional water balance model for micro-irrigated hedgerow tree crops. *Irrigation Science*, *22*(3–4), 157–170.

Anyia, A. O., & Herzog, H. (2004). Water-use efficiency, leaf area and leaf gas exchange of cowpeas under mid-season drought. *European Journal of Agronomy*, *20*(4), 327–339.

Balasubramanian, A. (2014). *Agro-Ecological Zones*. (March).

Barrett-Lennard, P., Dolling, P., & Ferris, D. (2010). *The advantages and disadvantages of pasture cropping in Farmer ' s perceptions*.

Baumann, D. T., Bastiaans, L., Goudriaan, J., Van Laar, H. H., & Kropff, M. J. (2002). Analysing crop yield and plant quality in an intercropping system using an eco-physiological model for interplant competition. *Agricultural Systems*, *73*(2), 173–203.

Bedoussac, L., & Justes, E. (2011). A comparison of commonly used indices for evaluating species interactions and intercrop efficiency: Application to durum wheat-winter pea intercrops. *Field Crops Research*, *124*(1), 25–36.

Beletse, Y. G. (2006). *Modelling the soil water and salt balance of planted pastures irrigated with sodium sulphate rich mine effluent*. University of Pretoria.

Bertness, M. D., & Callaway, R. (1994). Positive interactions in communities. *Trends in Ecology and Evolution*, *9*(5), 187–191.

Brisson, N., Bussiere, F., Ozier-Lafontaine, H., Tournebize, R., & Sinoquet, H. (2004). Adaptation of the crop model STICS to intercropping. Theoretical basis and parameterisation N. *Agronomie, 24*(24), 409–421.

Bruce, S. E., Howden, S. M., Graham, S., Seis, C., Ash, J., & Nicholls, A. O. (2005). *Pasture-cropping: Effect on biomass, total cover, soil water and nitrogen*. (Chittelborough 1992), 141–147.

Caldwell, R. M., & Hansen., J. W. (1993). Simulation of multiple cropping systems with CropSys. In *Systems approaches for agricultural development 2* (p. 397–412.). Springer Science & Business Media.

Campbell G. S., & Diaz, R. (1988). *Simplified Soil-Water Balance Models to Predict Crop Transpiration* (F. R. Bidinger & C. Johansen, Eds.). Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics.

Carberry, P. S., McCown, R. L., Muchow, R. C., Dimes, J. P., Probert, M. E., Poulton, P. L., & Dalgliesh, N. P. (1996). Simulation of a legume ley farming system in northern Australia using the Agricultural Production Systems Simulator. *Australian Journal of Experimental Agriculture*, *36*(8), 1037–1048.

Casper, B. B., & Jackson, R. B. (1997). Plant competition underground. *Annu. Rev. Ecol. Syst.*, *28*, 545–570.

Chaves, M. M., Pereira, J. S., Maroco, J., Rodrigues, M. L., Ricardo, C. P. P., Osório, M. L., … Pinheiro, C. (2002). How plants cope with water stress in the field. Photosynthesis and growth. *Annals of Botany*, *89*(SPEC. ISS.), 907–916.

Chikowo, R., Corbeels, M., Tittonell, P., Vanlauwe, B., Whitbread, A., & Giller, K. E. (2008). Aggregating field-scale knowledge into farm-scale models of African smallholder systems: Summary functions to simulate crop production using APSIM. *Agricultural Systems*, *97*(3), 151–166.

Christine Jones. (1999). Cropping native pasture and conserving biodiversity: a potential technique. In *Conservation and Production in Grassy Landscapes.* Clare, South Australia.

Colom, M. R., & Vazzana, C. (2001). Drought stress effects on three cultivars of Eragrostis curvula: Photosynthesis and water relations. *Plant Growth Regulation*, *34*(2), 195–202.

Conway, G., & Toenniessen, G. (1999). Feeding the world in the twenty-first century. *Nature*, *402*(6761 Suppl), C55–C58.

Corbett, E. S., Crouse, & Robert P. (1968). Rainfall interception by annual grass and chaparral . . . losses compared. *U.S. Forest Serv. Res. Paper PSW*.

Coucheney, E., Buis, S., Launay, M., Constantin, J., Mary, B., & Cort, D. (2015). Environmental Modelling & Software Accuracy , robustness and behavior of the STICS soil e crop model for plant , water and nitrogen outputs : Evaluation over a wide range of agro-environmental conditions in France. *Environmental Modelling & Software*, *64*(64), 177–190.

Craig, P. R., Badgery, W., Millar, G., & Moore, A. (2015). Achieving modelling of pasture-cropping systems with APSIM and GRAZPLAN. *Proceedings of the 17th ASA Conference - Building Productive, Diverse and Sustainable Landscapes*, (September), 2013–2016.

Descheemaeker, K., Amede, T., & Haileslassie, A. (2009). *Livestock and water interactions in mixed crop-livestock farming systems of sub-Saharan Africa: interventions for improved productivity*.

Finlayson, J. D., Lawes, R. A., Metcalf, T., Robertson, M. J., Ferris, D., & Ewing, M. A. (2012). A bio-economic evaluation of the profitability of adopting subtropical grasses and pasture-cropping on crop-livestock farms. *Agricultural Systems*, *106*(1), 102–112.

Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., & Holling, C. S. (2004). Regime Shifts, Resilience, and Biodiversity in Ecosystem Management. *Annual Review of Ecology, Evolution, and Systematics*, *35*(2004), 557–581.

Fukai, S., & Trenbath, B. R. (1993). Processes determining intercrop productivity and yields of component crops. *Field Crops Research*, *34*(3–4), 247–271.

Glatzel, K., Conway, G., Alpert, E., & Brittain, S. (2014). *No ordinary matter: Conserving, restoring and enhancing Africa's soils*. (December), 40.

Glover, J., Duggan, J., & Jackson, L. (2010). *A novel perennial pasture and winter wheat conservation agriculture intercrop system for central USA*. 1–4.

Goldberg, D. E. (1996). Competitive ability: Definitions, contingency and correlated traits. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *351*(1345), 1377–1385.

Hacker, R. B., Robertson, M. J., Price, R. J., & Bowman, A. M. (2009). Evolution of mixed farming systems for the delivery of triple bottom line outcomes: A synthesis of the Grain & Graze program. *Animal Production Science*, *49*(10), 966–974.

Hatfield, J. L., Sauer, T. J., & Prueger, J. H. (2001). Managing Soils to Achieve Greater Water Use Efficiency : A Review Managing Soils to Achieve Greater Water Use Efficiency : A Review. *Agronomy Journal*, *93*, 271–280.

Heuzé, V., Tran, G., Giger-Reverdin, S., Renaudeau, D., Bastianelli, D., & Lebas, F. (2015). Cowpea (Vignia unguiculata) forage. Feedipedia, a programme by INRA, CIRAD, AFZ and FAO. Retrieved from Feedipedia website:

Holmgren, M., Scheffer, M., & Huston, M. A. (2009). The Interplay of Facilitation and Competition in Plant Communities. *Ecology*, *78*(7), 1966–1975.

Huth, N. I., Bristow, K. L., & Verburg, K. (2012). Swim3: Model use, calibration, and validation. *American Society of Agricultural and Biological Engineers*, *55*(4), 1303–1313.

Johnston, W. H., Koen, T. B., & Shoemark, V. F. (2002). Water use, competition, and a temperate-zone C4 grass (Eragrostis curvula (Schrad.) Nees. complex) cv. Consol. *Australian Journal of Agricultural Research*, *53*(6), 715–728.

Jones, H. G. (1998). Stomatal control of photosynthesis and transpiration. *J Exp Bot*, *49*(July 1997), 387–398.

Kabirizi, J., Ziiwa, E., Mugerwa, S., Ndikumana, J., & Nanyennya, W. (2013). *Dry season forages for improving dairy production in smallholder systems in Uganda*. *1*, 212–215.

Keating, B. A., Carberry, P. S., Hammer, G. L., & Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N., Meinke, H., Hochman, Z. and McLean, G. (2003). *An overview of APSIM, a model designed for farming systems simulation* (pp. 267–288). pp. 267–288.

Kiniry, J. R., Williams, J. ., Gassman, P. ., & Debaeke, P. (1992). A General, Process-Oriented Model for Two Competing Plant Species. *Transactions of the ASAE*, *35*(3), 801.

Kirkham, M. B. (2005). Water-Use Efficiency. *Encyclopedia of Soils in the Environment*, 315–322.

Knörzer, H., Graeff-Hönninger, S., Müller, B. U., Piepho, H.-P., & Claupein, W. (2010). A Modeling Approach to Simulate Effects of Intercropping and Interspecific Competition in Arable Crops. *International Journal of Information Systems and Social Change*, *1*(4), 44–65.

Lawes, R. A., Ward, P. R., & Ferris, D. (2014). Pasture cropping with C4 grasses in a barley-lupin rotation can increase production. *Crop and Pasture Science*, *65*(10), 1002–1015.

Lightfoot, C. W. F., Dear, K. B. G., & Mead, R. (1987). *lIntercropping sorghum with cowpea in dryland farming systems in Borswana. II. Comparative stability of alternative cropping systems*. *23*, 435–442.

Lightfoot, C. W. F., & Tayler, R. S. (1987). Intercropping sorghum with cowpea in dryland farming systems in Botswana. I. Field experiments and relative advantages of intercropping. *Experimental Agriculture*, *23*(04), 425–434.

Liu Guobin, L., Kemp, D. R., & Liu, G. B. (1992). Water stress affects the productivity, growth components, competitiveness and water relations of phalaris and white clover growing in a mixed pasture. *Australian Journal of Agricultural Research*, *43*(3), 659–672.

Lodge, G. M., & Mccormick, L. H. (2006). Pasture cropping in northern NSW – do the numbers for plant available water stack up? *Proceedings of the 25th Annual Conference of The Grassland Society of NSW*, (1), 166–168.

Lowenberg-DeBoer, J., Krause, M., Deuson, R., & Reddy, K. C. (1991). Simulation of yield distributions in millet-cowpea intercropping. *Agricultural Systems*, *36*(4), 471–487.

Maestre, F. T., Valladares, F., & Reynolds, J. F. (2005). Is the change of plant-plant interactions with abiotic stress predictable? A meta-analysis of field results in arid environments. *Journal of Ecology*, *93*(4), 748–757.

Marais, D., Rethman, N., & Annandale, J. (2006). Dry matter yield and water use efficiency of five perennial subtropical grasses at four levels of water availability. *African Journal of Range and Forage Science*, *23*(3), 165–169.

Millar, G. D., & Badgery, W. B. (2009). Pasture cropping: A new approach to integrate crop and livestock farming systems. *Animal Production Science*, *49*(10), 777–787.

Morris, R. A., & Garrity, D. P. (1993a). Resource capture and utilization in intercropping; non-nitrogen nutrients. *Field Crops Research*, *34*(3–4), 319–334.

Morris, R. A., & Garrity, D. P. (1993b). Resource capture and utilization in intercropping: water. *Field Crops Research*, *34*(3), 303–317.

Mureithi, S. M., Verdoodt, A., Njoka, J. T., Gachene, C. K. K., & Ranst, E. Van. (2015). *Benefits Derived From Rehabilitating a Degraded Semi-Arid Rangeland in Communal Enclosures , Kenya*.

Murungweni, C., Van Wijk, M. T., Smaling, E. M. A., & Giller, K. E. (2016). Climate-smart crop production in semi-arid areas through increased knowledge of varieties, environment and management factors. *Nutrient Cycling in Agroecosystems*, *105*(3), 183–197.

Natarajan, M., & Willey, R. W. (1986). *Field Crops Research The effects of water stress on yield advantages of intercropping systems*. *13*, 117–131.

Njoka-Njiru, E. N., Njarui, M. G., Abdulrazak, S. A., & Mureithi, J. G. (2006). Effect of intercropping herbaceous legumes with napier grass on dry matter yield and nutritive value of the feedstuffs in semi-arid region of Eastern Kenya. *Agricultura Tropica et Subtropica*, *39*(4), 255–267.

Nkonya, E., Gerber, N., von Braun, J., De Pinto, A., & Braun, J. Von. (2011). Economics Of Land Degradation. *IFRI Issue Briefs*, *68*(September), 1–7.

O’Callaghan, J. R., Maende, C., & Wyseure, G. C. L. (1994). Modelling the intercropping of maize and beans in Kenya. *Computers and Electronics in Agriculture*, *11*(4), 351–365.

Ofori, F., & Stern, W. R. (1987). Cereal–Legume Intercropping Systems. *Advances in Agronomy*, *41*(C), 41–90.

Orin Ray Clark. (1940). Interception of Rainfall by Prairie Grasses, Weeds, and Certain Crop Plants.

Ecological Society of America, *10*(2), 243–277.

Ozier-Lafontaine, H. F., Lafolie, F., Bruckler, L., Tournebize, A., & Mollier, A. (1998). Modelling competition for water in intercrops: theory and comparison with field experiments. *Plant and Soil*, *204*, 183–201.

Ozier-Lafontaine, H. F., Lafolie, F., Bruckler, L., Tournebize, A., & Mollier, A. (1999). Modeling soil-root water transport and competition for single and mixed crops. *Plant and Soil*, *210*, 127–143.

Rees, D. J. (1986a). Crop growth , development and yield in semi- arid conditions in botswana . ii . The effects of intercropping sorghum bicolor with vigna unguiculata. *Experimental Agriculture*, *22*, 169–177.

Rees, D. J. (1986b). The effects of population density and intercropping with cowpea on the water use and growth of sorghum in semi-arid conditions in Botswana. *Agricultural and Forest Meteorology*, *37*(4), 293–308.

Rockström, J. (2000). Water Resources Management in Smallholder Farms in Eastern and Southern Africa : an Overview. *Phys. Chem. Earth (B)*, *25*(3), 275–283.

Rockström, J., Barron, J., & Fox, P. (2002). Rainwater management for increased productivity among small-holder farmers in drought prone environments. *Physics and Chemistry of the Earth*, *27*(11–22), 949–959.

Rockström, J., Barron, J., & Fox, P. (2003). Water Productivity in Rain-fed Agriculture: Challenges and Opportunities for Smallholder Farmers in Drought-prone Tropical Agroecosystems. *Water Productivity in Agriculture: Limits and Opportunities for Improvement*, 145–162.

Schultze-Kraft, R., Rao, I. M., Peters, M., Clements, R. J., Bai, C., & Liu, G. (2018). Tropical forage legumes for environmental benefits: An overview. *Tropical Grasslands-Forrajes Tropicales*, *6*(1), 1.

Seis, C. (2006). Pasture cropping as a means to managing land. *Australian Organic Journal*, *Winter 200*(66), 42–43.

Sekhon, H. S., Singh, G., Sharma, P., & Bains, T. S. (2010). *Water Use Efficiency Under Stress Environments*.

Sengul, S. (2003). Performance of some forage grasses or legumes and their mixtures under dry land conditions. *European Journal of Agronomy*, *19*(3), 401–409.

Shepherd, K. D., Vanlauwe, B., Tittonell, P., Giller, K. E., & Leffelaar, P. A. (2005). Exploring diversity in soil fertility management of smallholder farms in western Kenya. *Agriculture, Ecosystems & Environment*, *110*(3–4), 166–184.

Silburn, D. M., Robinson, J. B., & Freebairn, D. M. (2007). Why restore marginal cropland to permanent pasture? Land resource and environmental issues. *Tropical Grasslands*, *41*(3), 139–153.

Sinclair, T. R., Tanner, C. B., & Bennett, J. M. (1984). Water-Use Efficiency in Crop Production. *BioScience*, *34*(1), 36–40.

Snaydon R, W., & Satorre E, H. (1989). Bivariate diagrams for plant competition data modifications and interpretation. *Journal of Applied Ecology*, *26*(3), 1043–1057.

Snyman, H. A. (1990). *The influence of range condition on the hydrological characteristics in a semi-arid rangeland*. (106), 93–94.

Snyman, H. A. (1994). Evapotranspiration, water-use efficiency and quality of six dryland planted pasture species and natural vegetation, in a semi-arid rangeland. *African Journal of Range and Forage Science*, *11*(3), 82–88.

Snyman, H. A. (1999). Quantification of the soil-water balance under different veld condition classes in a semi-arid climate. *African Journal of Range Forage Science*, *16*(2), 108.

Snyman, H. A. (2005). Rangeland degradation in a semi-arid South Africa - I: Influence on seasonal root distribution, root/shoot ratios and water-use efficiency. *Journal of Arid Environments*, *60*(3), 457–481.

Valbuena, D., Erenstein, O., Homann-Kee Tui, S., Abdoulaye, T., Claessens, L., Duncan, A. J., … van Wijk, M. T. (2012). Conservation Agriculture in mixed crop-livestock systems: Scoping crop residue trade-offs in Sub-Saharan Africa and South Asia. *Field Crops Research*, *132*, 175–184.

Van Duivenbooden, N., Pala, M., Studer, C., Bielders, C. L., & Beukes, D. J. (2000). Cropping systems and crop complementarity in dryland agriculture to increase soil water use efficiency: a review. *NJAS - Wageningen Journal of Life Sciences*, *48*(3), 213–236.

Vandermeer, J., & Schultz, B. (1990). *Agroecology* (S. R. Gliessman, Ed.).

Vohland, K., & Barry, B. (2009). A review of in situ rainwater harvesting (RWH) practices modifying landscape functions in African drylands. *Agriculture, Ecosystems and Environment*, *131*(3–4), 119–127.

Wahua, T. A. T., Babalola, O., & Aken’ova, M. E. (1981). Intercropping morphologically different types of maize with cowpeas: LER and growth attributes of associated cowpeas. *Experimental Agriculture*, *17*(4), 407–413.

Ward P. R., Lawes, R. A., & Ferris, D. (2014). Soil-water dynamics in a pasture-cropping system. *Crop and Pasture Science*, *65*(10), 1016–1021.

White, C. (2012). *Pasture Cropping*. *42*(7).

Willey, R. W. (1990). Resource use in intercropping systems. *Agricultural Water Management*, *17*(1), 215–231.

Winterbottom, R., Reij, C., Garrity, D., Glover, J., Hellums, D., McGahuey, M., & Scherr, S. (2013). Improving land and water management. *World Resources Institute*, (October), 1–44.

Yaacob, O., & Blair, G. J. (1981). Effect of legume cropping and organic matter accumulation on the infiltration rate and structural stability of a granite soil under a simulated tropical environment. *Plant and Soil*, *60*(1), 11–20.

3. Adaptation and Application of Soil Water Balance Modelling to Improve Understanding of Below-Ground Competition in a Cowpea-Pasture Intercrop.

R N Orford[1], N Benadé[3], M van der Laan[2], J Annandale[2], F Asch[1].

[1] The Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg-Institute), University of Hohenheim: Crop Water Stress Management in the Tropics and Subtropics, Hohenheim University. Garbenstr. 13, 70599 Stuttgart, Germany,

[2] The institute of Plant Production and Agroecology in the Tropics and Subtropics, Department of Plant and Soil Sciences, University of Pretoria, Private Bag X20 Hatfield, Pretoria 0028.

[3] NB Systems. NB Systems cc, Sinoville, Pretoria, South Africa, E-mail: nicob@mweb.co.za

3.1 Introduction

3.1.1 Problem Statement

Due to the costly nature of running multiple agricultural field trials to appropriately assess the potential of pasture cropping (PaCr) in various unpredictable conditions, modelling PaCr in the subtropical context allows the cropping system to be “stress tested” across the full range of climatic conditions and different soil types. This will give further insight into the robustness or fallibility of the model in the broadest scope possible. No modelling has been done on pasture cropping (PaCr) in summer rainfall conditions, nor has a South African developed model such as the soil water balance model (SWB) been applied to PaCr. Lastly SWB was initially developed for monocropping systems and this research offered the opportunity to broaden the functionality of the model. Lastly, less attention has been paid to competition for water in intercropping modelling, with all but a few looking at competition for radiation (Knörzer, Graeff-Hönninger, Müller, Piepho, & Claupein, 2010).

3.1.2 The Objectives

The objectives were to firstly present the intercropping adaptations of the SWB model to simulate an intercropping system such as PaCr. Secondly the model simulations are then to be compared with observed yield results of the field trials performed in 2013-14 and 2015 to assess the level of statistical integrity. Thirdly the simulations will be used to enrich the understanding of SW dynamics of the PaCr system by providing simulated data that was not measured in the trial.

3.1.3 Literature Review

The focus of the adaptations to SWB was primarily on SW dynamics. This was for the reasons that the trials in 2013-14 and 2015 described previously, ensured that water was the only limiting resource by adding fertiliser and assuming radiation was in abundance. This is further supported in that the abundance of radiation (18.75 MJm^2s^{-1}) is higher in the sub-tropics than the saturation point for both cowpea and *E. curvula* (10 -18.8 MJm^2s^{-1}) (Anyia & Herzog, 2004; Colom & Vazzana, 2001). Due to the negligible height difference between cowpea and pasture for a greater portion of the trial, shading out of either crop was assumed to have a negligible effect relative to the competition for water. Literature also suggests that below ground competition for water in mixed plant and cropping systems far outweighs the competition for radiation and nutrients in semi-arid subtropics (Holmgren et al., 2009). Consequently, water is the pivotal driver of yield and competition. Due to this also being the first adaptation toward an intercropping model for row crops and due to the complexity of resource competition for water, nutrients and radiation in an intercropping system, this analysis was limited to understanding the SW dynamics of the cropping systems.

The literature on the dynamics of competition for water in intercropping, let alone PaCr, is limited. The main models that consider the competition for water in intercropping to a lesser or greater degree can be seen in Table 3-1. There is a surprising level of similarity in the approaches that models have used to simulate competition in intercropping systems. When considering the above ground competition, the simple one-dimensional (1D) approach with regard to the interception of radiation involves the partitioning of interception based on the individual crop's coefficient and the leaf area index (LAI) which in turn partitions transpiration. Some models, such as the agricultural production simulator (APSIM) model have taken this concept one step further and partitioned fractional radiation interception (FI) over *n* canopy layers depending on the number and height of species in question, (Adiku, Carberry, Rose, McCown, & and Braddock, 1995; Carberry et al., 1996). Ozier-Lafontaine *et al* (1998) created a 2-D approach of a "turbid medium analogy" with contiguous cells with radiation interception related to the geometrical structure of the crop.

In below ground competition, there is an overarching approach that involves ≥ 2 crops taking up water from the same reservoir where the order of uptake is determined by the order of planting (Kiniry, Williams, Gassman, & Debaeke, 1992; O'Callaghan, Maende, & Wyseure, 1994). APSIM originally retained the same reservoir approach, however, the order of water uptake per crop was set to alternate on a daily basis to reduce the bias from precedence in daily orders of calculations (Adiku et al., 1995). The more recent SWIM3 adaptations to APSIM "provides a one- dimensional simulation of water fluxes through a numerical solution to the Richards equation" (Huth, Bristow, & Verburg, 2012). Ozier-Lafontain *et al*.,(1998) provides a 2D modified Penman-Monteith approach with a 2D soil root contact map to determine water uptake. The only model that has specifically modelled PaCr involves the GRAZPLAN/APSIM model which is based on APSIM (Craig, Badgery, Millar, & Moore, 2015).

Table 3-1 Summary comparison of intercropping models. Abbreviations are fractional interception (FI), crop coefficient (Kc) and Leaf Area Index (LAI). References: **(1)** (Kiniry et al., 1992),**(2)** (Lowenberg-DeBoer, Krause, Deuson, & Reddy, 1991) **(3)** (Keating, Carberry, Hammer, & Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N., Meinke, H., Hochman, Z. and McLean, 2003), **(4)** (Huth et al., 2012), **(5)** (Adiku et al., 1995), **(6)** (Brisson, Bussiere, Ozier-Lafontaine, Tournebize, & Sinoquet, 2004), **(7)**(Caldwell, R. M. & Hansen., 1993), **(8)**(O' Callaghan et al., 1994), **(9)** (Ozier-Lafontaine, Lafolie, Bruckler, Tournebize, & Mollier, 1999), **(10)** (Baumann, Bastiaans, Goudriaan, Van Laar, & Kropff, 2002)

Model	Crop Mixture Type	Species	Time steps	Below Ground					Above Ground				Reference
				Dimension	Soil Layers	Reservoir	Root system	Water Uptake	Dimension	Canopy Layers	Partitioning of radiation interception	Partitioning of Et_o	
ALMANAC	Crop/Crop: Maize and soybean	2	1 day	1	1	Common	Mixed	1st Crop	1	1	LAI weighted by Kc	FI	1
GROWIT	Crop/Crop: Millet and cowpea	2	1 day	1	1	Common	Mixed	2nd Crop	1	1	LAI weighted by shortest crop	FI	2
APSIM	Crop/Crop	n	1 day	1	N	Common	Mixed	Alternates daily	1	N	(extinct_coeff * LAI) dissipated - through the layers	FI	3
APSIM (SWIM 3)	Crop/Crop	n	1 day	1	N	Common	Mixed	Runge-Kutta calculation (Huth et al., 2012)	1	N	(extinct_coeff * LAI) dissipated through the layers	FI	4
AUSIM-MAIZE	Crop/Crop	2	1 day	1	1	Common	Mixed	Runge-Kutta calculation (Huth et al., 2012)	1	2	Lai weighted by shading of tallest crop.	FI	5
STICS	Crop/Crop or Tree/Crop	2	1 day	1	N	Common	Mixed with inbuilt root plasticity function.		1	2	geometric shape radiation balance.	FI	6
CROPSYS	Crop/Crop	2	1 day	1	N	Common	Separate		1	2	Radiation Balance	FI	7
SODCOM	Maize and beans	2	1 day	1	N	Common	Mixed	1st Crop	1	1	LAI weighted by shading of tallest crop.	Kc	8
WATERCOMP		2	Hour/Sub-hour	2	N	Common	Mixed		2	N	Contiguous cells with radiation interception related to the geometrical structure of the crop.	Penman-Montheith	9
INTERCOM	Crop/Crop	2	1 day	1	1	Common	Separate	No competition water uptake uninhibited.	1	N	INTERROW radiation interception module (Gijzen and Goudriaan (1989)).	FI	10

3.2 Model Description

The SWB model is a mechanistic, generic crop model which was developed as a real-time irrigation-scheduling tool (Annandale, Jovanovic, Campbell, Du Sautoy, & Benadé, 2003). It was based on a generic crop version of the NEWSWB (Campbell G. S. & Diaz, 1988). The model calculates crop growth and water balances using soil, weather and crop units. The evapotranspiration is calculated according to the Penman-Monteith grass reference method as recommended by the Food and Agricultural Organisation (Allen, 1998). The soil-water balance can be modelled using either a cascading soil-water balance or a finite difference model (Annandale, Benadé, Jovanovic, & Du Sautoy, 1999). Daily crop dry matter accumulation was taken as the lower value of either radiation-limited growth (Monteith, 1977) or water-limited growth (Sinclair et al., 1984). Thermal time is used to delineate and calculate phenology and partitioning with the effect of water stress accounted for through the use of a stress factor.

3.2.1 Model Input Variables and Parameters

Weather data including daily values of minimum and maximum air temperature and humidity, wind speed, incoming solar radiation and precipitation are used to run the model. Details of model input variables and parameters for crop growth and water are available in *Annandale et al* (2003).

3.2.2 Adaptations in the Model

3.2.2.1 Water Uptake Adaptation

The primary adaptation to the SWB model to adapt it from a single crop to an intercrop simulation was to add *E. curvula* into a single day step (see figure 3-1). The standard version of SWBsci follows a single crop day step as seen in figure 3-1. The crops and fields are initiated, then field and crop variables are updated from the previous day. Precipitation and irrigation variables are updated followed by the evapotranspiration (ETo) and climate data.

To adjust the model to the PaCr cropping system so that water is taken up by two intercropped species within the same day step, a second crop module was added within a day step after the results of the first crop were stored. The second crop follows the same steps as described for crop 1, they are stored and then the next day is initiated. The order of cowpea being the first crop to take up water in a day step was based on cowpea being isohydric and known to control water loss by tight stomatal control under water limiting conditions (Jones, 1998) and having shorter roots whereas *E. curvula* tends to show more anisohydric properties including leaf rolling and reduction in leaf area rather than immediate stomatal closure (Colom & Vazzana, 2001) . This is important because if there in a finite amount of moisture remaining on a particular day, the first crop will benefit more than the second crop and thus if there is no consideration for this order of uptake there may be a cumulative bias that may skew yield outcomes.

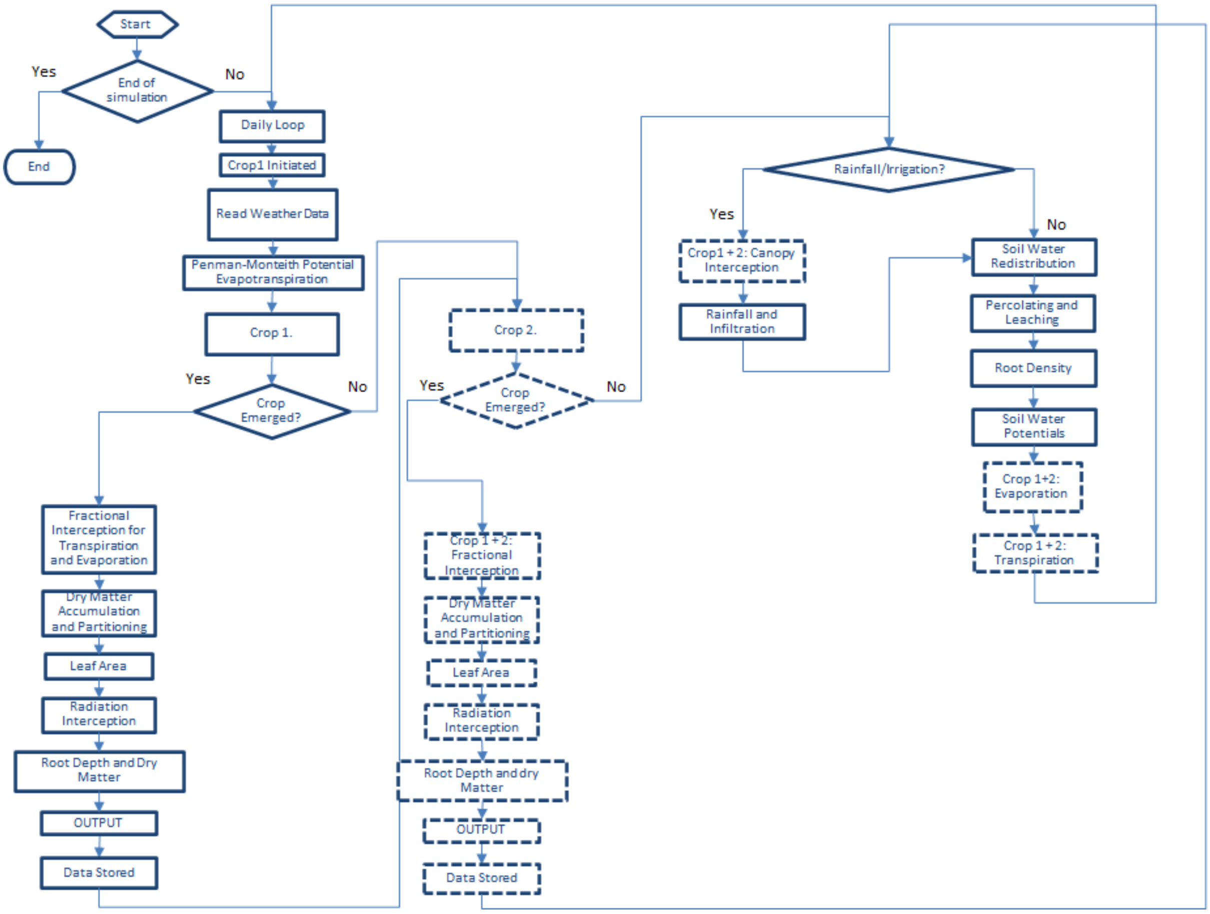


Figure 3-1 Schematic flow diagram of the calculation units of one-day cycle of the SWB model. The shapes with dashed outlines were added to model day step.

3.2.2.2 Canopy Radiation Extinction Coefficient

$$\boldsymbol{FI = 1 - e^{(-Kc*LAI)}}$$

$$\boldsymbol{For\ (FI_{crop\ i} + FI_{crop\ j}) > 1}$$

$$\boldsymbol{FI_{crop\ i} = \frac{FI_{crop\ i}}{FI_{crop\ i} + FI_{crop\ j}}}$$

$$\boldsymbol{FI_{crop\ j} = \frac{FI_{crop\ j}}{FI_{crop\ i} + FI_{crop\ j}}} \qquad \text{Eq. 10}$$

To ensure that fractional interception of radiation did not exceed one, once the sum of fractional interception of both crops ($\mathrm{FI}_{\mathrm{crop\ i}}$ and $\mathrm{FI}_{\mathrm{crop\ j}}$) exceeded one, $FI_{crop\ i}$ or $FI_{crop\ j}$ was divided by the sum of the overall combined $FI_{crop\ i+j}$ of both crops.

3.2.2.3 Potential Evapotranspiration

To ensure that the combined potential transpiration (PT) of two crops ($CombinedPT$) did not exceed the maximum potential evapotranspiration ($CombinedPET$) determined by atmospheric demand, transpiration per crop was limited by a transpiration factor ($TransFactor$). $FItransp_i$ represents the fractional interception apportioned for transpiration.

$$\boldsymbol{CombinedPT = (FItransp_i \times PET_i) + (FItransp_j \times PET_j);}$$

$$\boldsymbol{CombinedPET = \frac{(PET_i + PET_j)}{2}}$$

$$\boldsymbol{If\ CombinedPET - CombinedPT < 0\ then}$$

$$\boldsymbol{TransFactor = \frac{CombinedPET}{CombinedPT}}$$

$$\boldsymbol{CombinedPT := (TransFactor \times CombinedPT)}$$

$$\boldsymbol{FItransp_i := FItransp_i \times TransFactor}$$

$$\boldsymbol{FItransp_j := FItransp_j \times TransFactor} \qquad \text{Eq. 11}$$

3.2.2.4 Evaporation

Evaporation ($PotEvap$) was adapted by subtracting the sum of both crops' fractional interception of radiation by photosynthetically active leaves ($FItransp_i + FItransp_j$) from one with the remainder determining the proportion of $CombinedPET$ available for evaporation.

$$\boldsymbol{PotEvap:\ (1 - (FItransp_i + FItransp_j)) \times CombinedPET} \qquad \text{Eq. 12}$$
$$\boldsymbol{For\ PotEvap < 0, PotEvap = 0}$$

3.2.2.5 Canopy Rainfall Interception

Due to combined crops intercepting rainfall, the rain interception parameter (*CanopyInt*) of either crop was multiplied by the FItransp and added. The rainfall interception potential of mulch was included into this parameter.

$$\boldsymbol{Soil.interDOY = (FItransp_i \times CanopyInt_i) + (FItrans_j \times CanopyInt_j)} \qquad \text{Eq. 13}$$

3.3 Data Collection

The rain fed trial consisted of three treatments including a cowpea monocrop (CM), established pasture (PM), and an additive pasture cropping (PaCr) setup of cowpea directly seeded into pasture (See Chapter 1).

Table 3-2 Agronomic information and experimental treatments of the field experiments

Growing season	2013-14	2015
Crop variety		
Eragrostis	Ermelo	Ermelo
Cowpea	Var. Agrinawa (indeterminate)	Var. Glenda (determinate)
Growing period	90 Days	90 Days
Sowing date	20/12/2013	15/01/2015
Row orientation	N-S	N-S
Plant density		
E. curvula	333333 ha^{-1}	333333 ha^{-1}
Cowpea	31250 ha^{-1}	31250 ha^{-1}
Row spacing		
E. curvula	Full coverage	
Cowpea	0.8 m x 0.4 m	0.8 m x 0.4 m
Plot size	100 m^2	18 m^2
Rep's.	4	4
Rainfall + irrigation	684.6	284.4
Basal fertiliser	100 kg N ha^{-1}, 50 kg P ha^{-1}, 100 kg K ha^{-1}	100 kg N ha^{-1}, 50 kg P ha^{-1}, 100 kg K ha^{-1}

3.3.1 Statistical Analysis

Statistical analyses were conducted to evaluate the performance of the model in predicting yield, LAI and SW deficit observations using the Root Mean Square Error (RMSE) which was then divided by the standard deviation of observed results. To allow for a range of tests as each delivers a different consensus, the chi-squared test was added indicating significance if α=0.05, d.f. 2<5.991 and was based on the final yield and LAI. The Mean Absolute Error (MAE) and the regression analysis (R2) were also added for the same aforementioned reason.

$$\boldsymbol{RMSE} = \sqrt{\sum \frac{(\boldsymbol{O_i} - \boldsymbol{P_i})^2}{\boldsymbol{n}}} \qquad \text{Eq. 14}$$

$$\boldsymbol{MAE} = \frac{\sum |(\boldsymbol{O_i} - \boldsymbol{P_i})|}{\boldsymbol{n}} \qquad \text{Eq. 15}$$

$$\boldsymbol{X^2\ Test} = \sum \frac{(\boldsymbol{O_i} - \boldsymbol{P_i})^2}{\boldsymbol{P}} \quad (\boldsymbol{\alpha} = \mathbf{0.05}) \qquad \text{Eq. 16}$$

$$\boldsymbol{R^2} = \frac{\sum(\hat{\boldsymbol{y}}_{\boldsymbol{i}} - \bar{\boldsymbol{y}})^2}{\sum(\boldsymbol{y_i} - \bar{\boldsymbol{y}})^2} \qquad \text{Eq. 17}$$

3.4 Results

3.4.1 *Crop Parameters*

Table 3-3 Table listing the parameters used in the trial for each crop per season.

Parameter	Cowpea Monocrop	Cowpea PaCr	Cowpea Monocrop	Cowpea PaCr	*E. curvula*	*E. curvula*
	(2013-14)	(2013-14)	(2015)	(2015)	(2013-14)	(2015)
Canopy extinction coefficient for total solar radiation (K_s) *	0.59	0.59	0.59	0.59	0.45	0.45
Dry matter/evapotranspiration ratio corrected for vapour pressure deficit DWR (Pa)*	3.5	3.5	3.5	3.5	4	4
Radiation conversion efficiency (g·MJ^{-1}) *	0.0013	0.0013	0.0013	0.0013	0.0009	0.0009
Base temperature (°C) *	10	10	10	10	10	10
Optimum temperature (°C) *	25	25	25	25	15	15
Cut-off temperature (°C) *	30	30	30	30	25	25
Emergence day degrees* (d °C) *	43	43	43	43	0[‡]	0[‡]
Day degrees at end of vegetative growth (d °C) *	2000	2000	700	700	1500	1500

Day degrees for maturity (d °C) *	2000	2000	1500	1500	1500	1500
Transition period day degrees (d °C)*	200	200	200	200	10	10
Day degrees for leaf senescence (d °C)*	1190	1190	1190	1190	700	700
Maximum crop height Hmax (m)*	0.55	0.55	0.55	0.55	0.5	0.5
Maximum root depth Rdmax (m)*	0.6	0.6	0.6	0.6	0.7	0.7
Specific leaf area SLA ($m^2 \cdot kg^{-1}$) ◊	17.3	17.3	17.79	17.35	8.2	8.2
Leaf-stem partition parameter p ($m^2 \cdot kg^{-1}$) ◊	1	1	0.34	0.7	0.3	0.3
Canopy Storage (mm)**	2	2	2	2	6	6
TDM at emergence (kg/m^2) *	0.0019	0.0019	0.0019	0.0019	0.04	0.03
Root growth rate ($m^2 \cdot kg^{-0.5}$) *	5	5	5	5	20	20

**(Annandale et al., 1999; Beletse, 2006)*
*** From literature (Corbett, Crouse, & Robert P, 1968; Orin Ray Clark, 1940) and includes mulch in the pasture-based systems.*
◊ Measured during the trial.
ǂ the emergence day degrees (d °C) for E. curvula was set to zero as the crop is already established.

The *E. curvula* crop parameters were mostly kept identical in both seasons (see Table 3-3) apart from initial biomass (TDM at emergence) which was adjusted to accommodate the slight deferred planting due to cowpea seed predation by birds and hence growth after mowing of *E. curvula* in the PaCr trial in 2013-14. Maximum root depth was adjusted by noting change in SW readings and root growth rate for *E. curvula* was set to be at full depth after one DAP to replicate an established grass crop. This was achieved by setting RGR to 20 $m^2 \cdot kg^{-0.5}$ which is fast enough to achieve maximum root depth in one day. The days to emergence of *E. curvula* was set to 0 due to the perennial nature of the pasture. The cowpea parameters that were measured included specific leaf area (SLA), maximum crop height and development stages were adjusted. Un-measured parameters were either taken from literature and/or adjusted to improve the goodness of fit. Some elements such as flowering were switched off in the 2013-14 season as the cowpea treatment did not flower and were switched on in 2015 (see day degrees at end of vegetative growth). Canopy storage was also increased to include mulch in the pasture thus being higher in the pasture parameters. These values were derived from Orin Ray Clark (1940).

3.4.2 Yields

The monocrop yields used to calibrate the model all showed good correlation (see Table 3-4), falling within the standard deviation. The results of the final yields of all treatments showed significant correlation with simulated results (Chi-Squared; $\alpha=0.05$, d.f. 2 = <5.991). The yield of the PaCr did have statistically adequate results in the 2013-14 season, whereas in the 2015 season the simulated yield was significantly below the observed yields for the *E. curvula* (Chi-Squared; $\alpha=0.05$, d.f. 2 = 8.93 which is greater than 5.991) and slightly above yields for the cowpea. There was also a large variation in *E. curvula* yields throughout, which can partially be attributed to the fields not being actively cultivated and there being various species of grasses interspersed amongst the *E. curvula*.

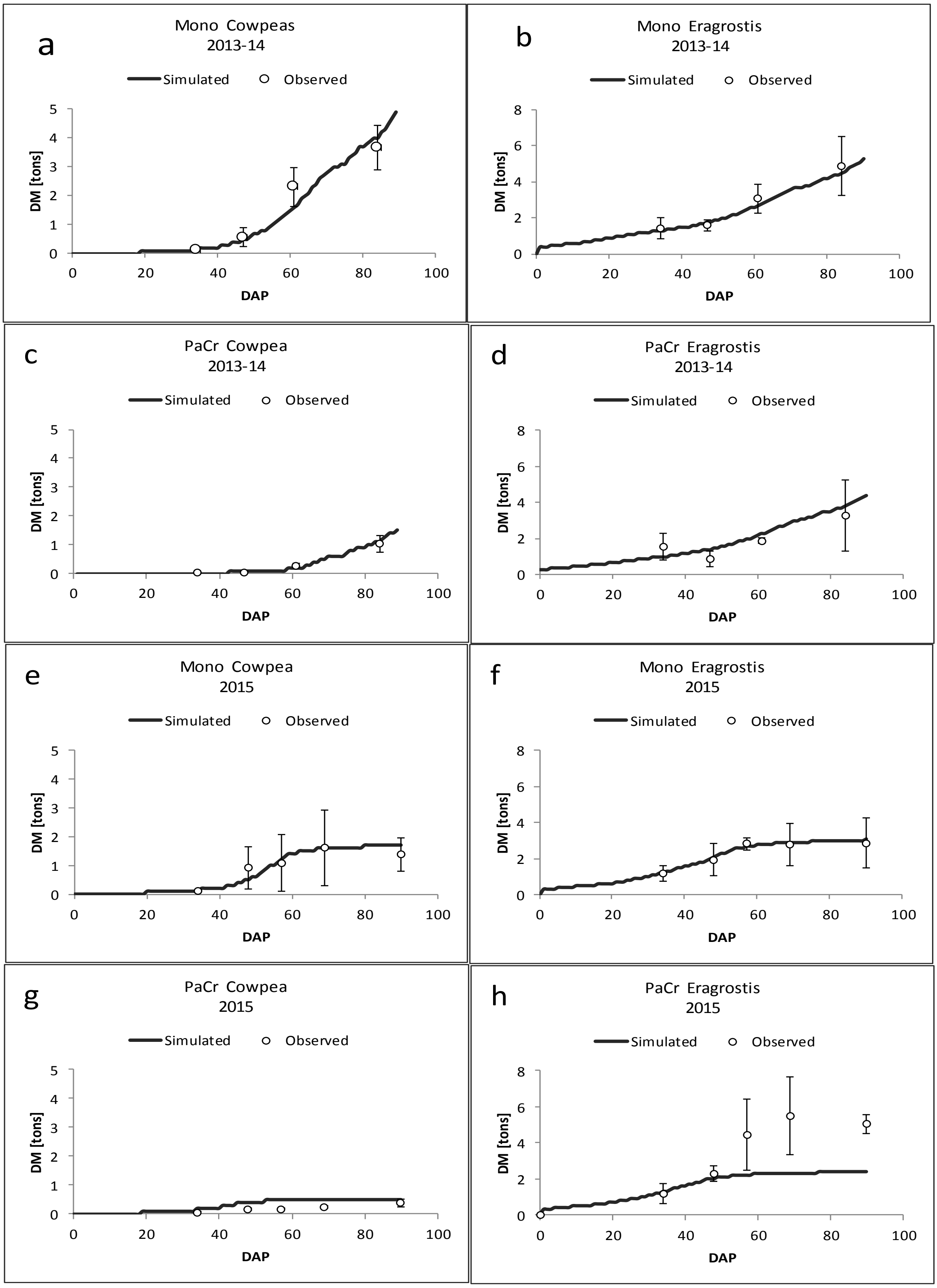


Figure 3-2 Observed versus simulated dry matter (DM) yields of the 2013-14 and 2015 trials. Graph a) Monocrop Cowpea 2013-14 b) Monocrop *E. curvula* 2013-14 c) PaCr Cowpea 2013-14 d) PaCr E. curvula 2013-14 e) Mono Cowpea 2015 f) Mono E. curvula 2015 g) PaCr Cowpea 2015 h) PaCr E. curvula 2015. Error bars represent standard deviation.

3.4.3 Leaf Area Index

Leaf area index is a crucial parameter because from the formula $\mathrm{FI} = 1 - \mathrm{e}^{(-\mathrm{Kc}*\mathrm{LAI})}$, fractional interception (FI) is calculated from LAI. FI determines what proportion of water is apportioned to evaporation and what portion is allocated to transpiration. This is crucial as the transpiration drives the yield function and evaporation is a key element in assessing whether PaCr is more water use efficient. This emphasises how necessary the statistical integrity for the LAI is. From Figure 3.3 it does show an adequate goodness of fit also confirmed by the Chi-Squared values all being less than the threshold significance of 5.991 for the final LAI value (see Table 3-4).

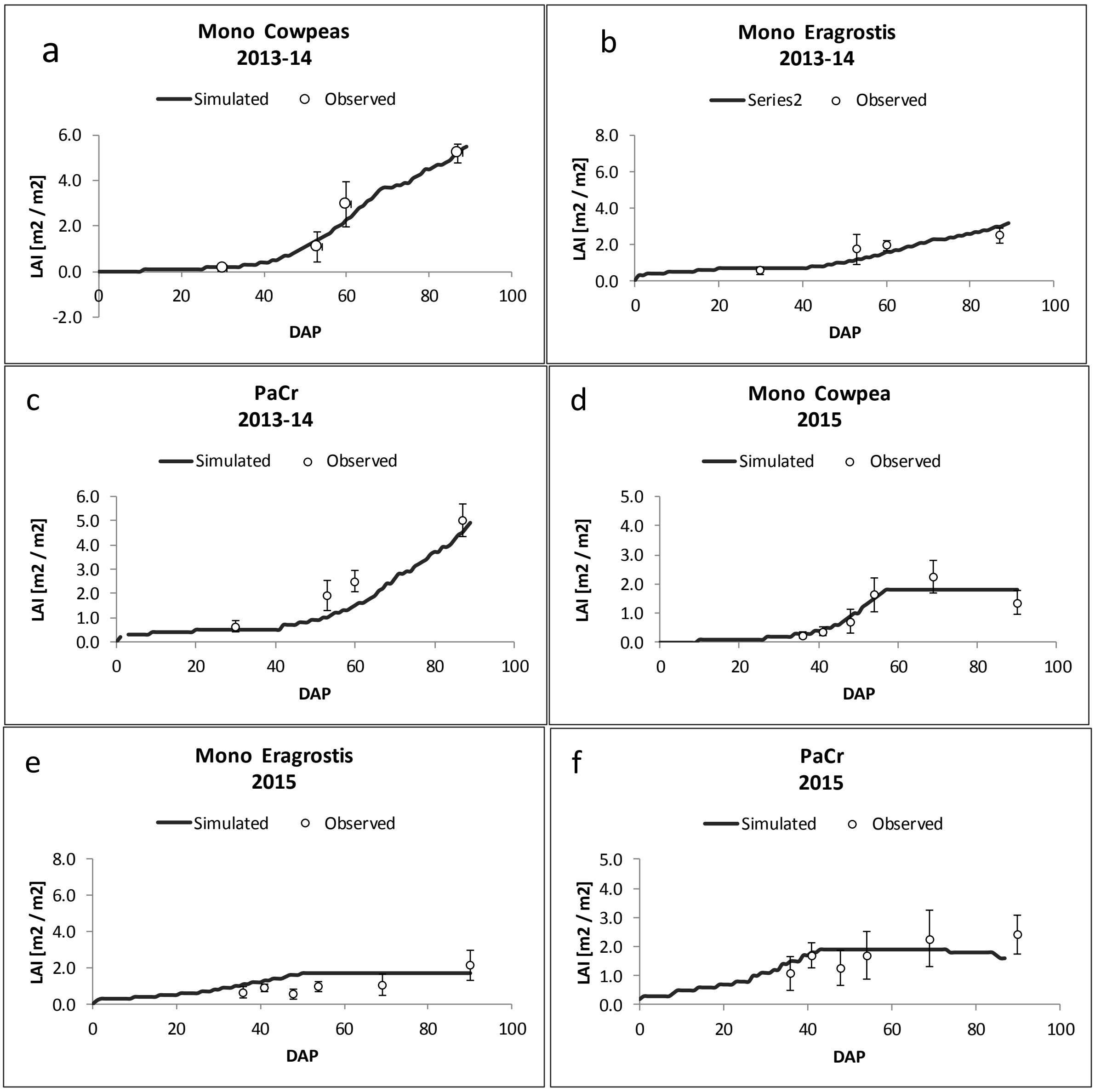


Figure 3-3 Observed versus simulated leaf area index (m^2/ m^2). Error bars represent standard deviation

3.4.4 Soil Water Levels

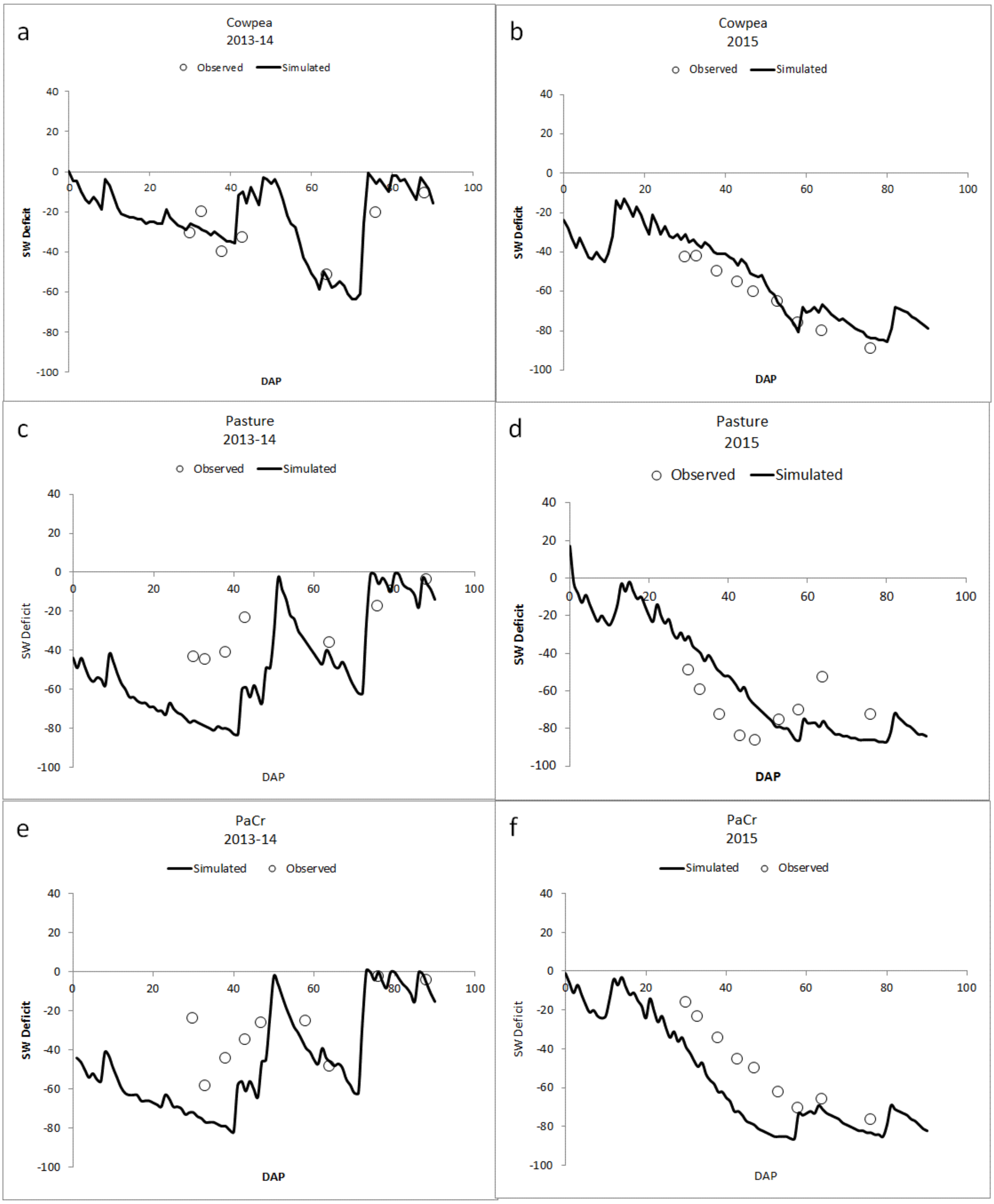


Figure 3-4 Observed versus simulated soil water (SW) deficit of the 2013-2014 and 2015 trials for the top 0.6 m.

The SW deficit graphs above present the visual indication of the goodness of fit with some degree of correlation. The 2013-14 season received far more rain which can be seen by the deficit being reduced significantly 50 days after planting. The second season shows the opposite effect whereby the deficit steadily increased to almost wilting point. From literature the cowpea SW deficit simulations are adequate (see Table 3-4). The pasture values capture the general pattern well enough to provide some information, however more accuracy would be desired in future.

3.4.5 *Statistical Results*

Table 3-4 Statistical analysis including the root-mean-squared-error (RMSE) and the mean absolute error (MAE), chi-squared test indicating significance if α=0.05, d.f. 2<5.991 and is notated by a * and the regression analysis (R2). The RMSE is normalised by dividing by standard deviation of the observed data (RSME/stdev-obs).

Yields	RMSE	MAE	Chi-Squared; α=0.05, d.f. 2<5.991 (Final Yield)	R^2	RSME/stdev-obs
(2013-14) Mono COWPEAS	0.39	0.07	0.37	0.94	24%
(2013-14) Mono ERAGROSTIS	0.29	0.07	1.26	0.98	18%
(2013-14) PaCr COWPEAS	0.06	0.01	0.16	0.99	6%
(2013-14) PaCr ERAGROSTIS	0.51	0.13	2.29	0.83	110%
(2015) Mono COWPEAS	0.24	0.04	0.59	0.86	42%
(2015) Mono ERAGROSTIS	0.15	0.03	1.26	0.97	20%
(2015) PaCr COWPEAS	0.23	0.04	0.16	0.89	197%
(2015) PaCr ERAGROSTIS	2.13	0.34	8.93	0.77	94%
LAI	**RMSE**	**MAE**	**Chi-Squared; α=0.05, d.f. 2<5.991 (Final LAI)**	**R^2**	**RSME/std-obs**
(2013-14) Mono COWPEAS	0.37	0.51	0.19	0.97	19%
(2013-14) Mono ERAGROSTIS	0.75	0.84	0.11	0.98	123%
(2013-14) PaCr	0.35	0.57	0.85	1.00	18%
(2015) Mono COWPEAS	0.28	0.47	0.02	0.86	38%
(2015) Mono ERAGROSTIS	1.04	1.01	0.09	0.34	350%
(2015) PaCr	0.69	0.79	0.36	0.18	219%
Deficits	**RMSE**	**MAE**		**R^2**	**RSME/std-obs**

(2013-14) Mono COWPEA	11.55	9.34	0.19	84%
(2013-14) Mono ERAGROSTIS	27.19	23.08	0.76	175%
(2013-14) PaCr	23.83	18.59	0.69	126%
(2015) Mono COWPEA	8.46	7.65	0.85	51%
(2015) Mono ERAGROSTIS	18.58	15.56	0.48	143%
(2015) PaCr	17.42	17.57	0.80	82%

In terms of yields, the normalised RMSE/stdev obs suggest that according to Coucheney *et al.* (2015) all but PaCr ERAGROSTIS (2013-14), PaCr COWPEAS (2015) and PaCr (2015) are satisfactory. However, from a classic regression analysis (R^2) criteria, the yield results are all above 0.7 and this is also confirmed by the visual goodness of fit and the chi-squared values seen in image Figure 3-2 and Table 3-4. Cowpea in PaCr in 2013-14 has the least variation of RMSE/stdev obs of 6 % from the simulated results, which is very low and considered as very good (Coucheney et al., 2015). PaCr COWPEAS (2015) on the other hand shows a RMSE/stdev obs of 197 % which is poor. This also is the only chi-squared value that exceeds chi-squared p-value of 5.9.

LAI values are all very satisfactory, however, due to the low variation in data, the RMSE/stdev obs of 350% would be considered as inadequate by Coucheney *et al.* (2015). However, the other parameters such as the chi-squared values and regression analysis (R^2) show satisfactory results.

With SW deficits, there is a bigger variation value due to the scale being in mm rather than tons. This variation can be normalised (RMSE/stdev obs) with the Mono Eragrostis (2013-14) which has a RMSE/stdev obs of 175 % which again is poor. The lowest is Mono Cowpea (2015) which only represents 51 % which is 1 % above a good classification (Coucheney et al., 2015). The values are not well correlated with the R^2 criteria where Mono COWPEA (2013-14) achieved a R^2 criteria of 0.19 whereas RMSE/stdev obs showed a result of 84 % which is not the highest value. However, RMSE/stdev obs does include the variation in the observed data whereas the R^2 criteria only expresses how close the data is to the fitted regression line. There is no correlation between R^2 and RMSE/stdev obs. Overall, the yield data is much more satisfactory (average normalised RSME of 64 %) versus than the SW deficit measurements of (average normalised RSME of 110%). The average normalised RMSE for monocrop yields was 26% whereas with PaCr it was 101 % suggesting that the complexity of intercropping does decrease the degree of model performance. While with SW deficits the difference is less pronounced, with monocrop soil, the water deficit is 113 % versus PaCr of 104%. The SWB adaptation is also the first attempt at making the SWB model an intercropping model which, when compared to other model such as STICS where the standardised RMSE is 33% for above-ground, dry matter is comparable to the SWB results. (Coucheney et al., 2015). However, the SW deficit values would require further attention to reduce the deviation from the predicted.

3.4.6 SWB Soil Water Component Outputs

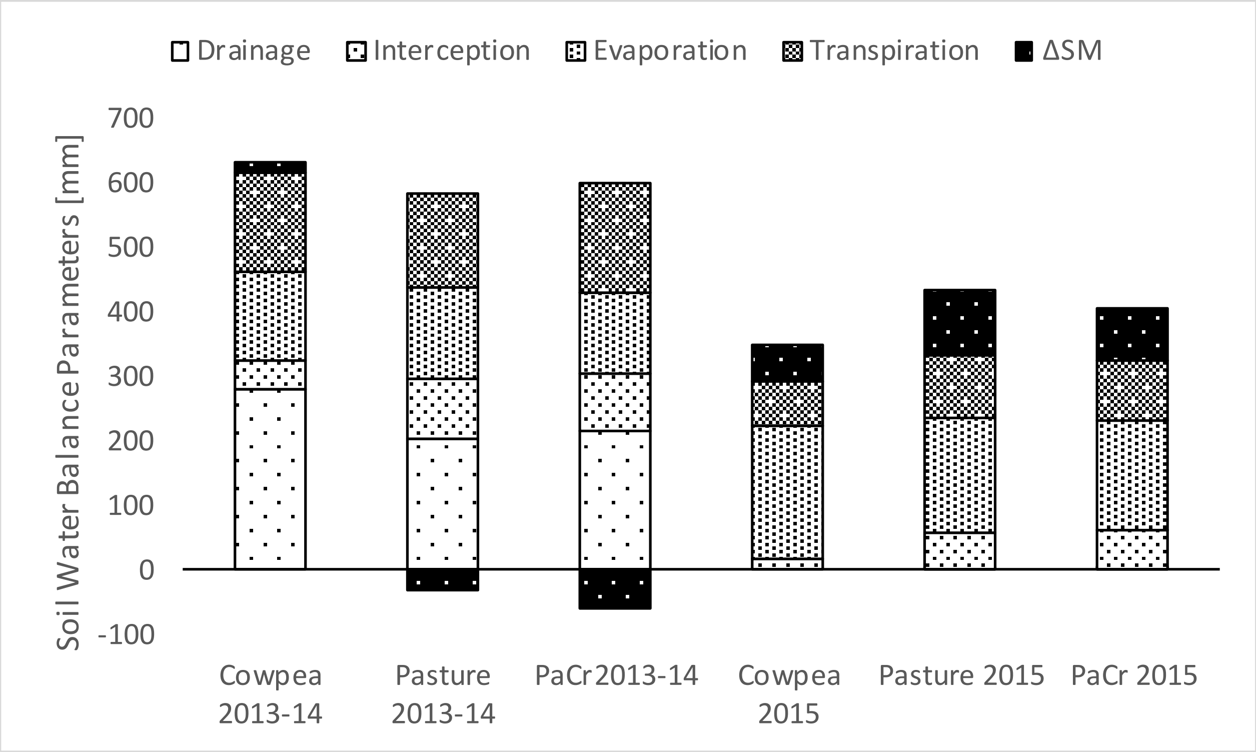


Figure 3-5 Simulated soil water outflows and inflows (mm) at the end of the season (90 DAP) for each cropping system across two seasons. Values above the x-axis represent out-flows and below the x-axis represent in-flows. ΔSW represents the change in soil water.

The 2013-14 SW losses including transpiration, evaporation, interception and drainage are much higher than that of 2015. However, due to the higher rainfall there is a positive ΔSW in the top 0.6 m except for CM. When considering the 2013-14 season, unproductive losses which include evaporation, drainage and interception, CM and PM lost 75% while PaCr lost 72%. However, PM and PaCr did retain 30 and 61 mm in the top 0.6 m of the soil. Transpiration, which is a productive outflow, amounted to 25% for CM and PM with 28% for PaCr. The major contributor to outflows in the 2013-14 season was the drainage which amounted to 45.68%, 34.45% and 35.69% for CM, PM and PaCr. This is attributed to the two large rainfall events of over 100 mm and maybe how the model dealt with excess water that may have been attributed to run-off which was not included.

In 2015, unproductive losses amounted 77%, 71% and 71% for CM, PM and PaCr. Transpiration amounted to 23%, 29% and 29% for PaCr. The major contributor to 2015's unproductive losses was evaporation which amounted to 70.38%, 53.84% and 52.10% for CM, PM and PaCr. Interception in the pasture-based system was relatively a very high unproductive loss amounting to over 15% while CM treatments were less than 7%.

Across seasons the major differences were that in 2013-14, there were significant drainage losses relative to very small losses in the 2015 season. But the 2015 season had 217%, 120% and 154% higher evaporative losses in 2015 relative to 2013-14.

3.5 Discussion

3.5.1 Adaptations in the model

The 1-dimensionsional (1D) cascading soil-water balance with a completely mixed root system has shown to be an adequate approach to modelling the high-density intercropping scenario of PaCr. The results of the yield and SW deficits across three different cropping systems and two different seasons has showed a degree of statistical significance with a good agreement with the measured data (see Table 4). This is more so for the yield data and less so for the SW deficit. Both crops draw from the same 1D layer where the amount of SW is reduced as it is taken up by each simulated crop over one day step. The SWB-intercropping version for this paper did not focus on the above ground dynamics of radiation competition and shading, only applying a 1D canopy with one layer which divided intercepted radiation between two crops' LAI factors which was expressed as FI. The sum of both crops FI was impartially limited to unity. Crop specific evapotranspiration calculations were partitioned by crop specific fractional interception. Transpiration thus determined the dry matter accumulation. The measured versus simulated yield results show that the measured yields corresponded well with the simulated yields, which suggests that the FI partitioning in the case of PaCr was successful for a first adaptation.

A majority of the parameters of the different crops were kept the same across a very wet 2013-14 season and an extremely dry 2015 season (see Table 3-3), the pasture was not perfectly homogenous with one species and soils were kept standardised across both seasons. These two extreme seasons allowed the unique opportunity to test the model under very varying circumstances. Due to this not being an attempt to validate the model but rather an attempt to verify SWB adaptations as described in the paper, it can be used to explore concepts of intercropping systems, in this the case the novel PaCr system. It has also provided insight into the strengths and weaknesses in this first adaptation attempt, allowing for more effective refinements to the model and flagging necessary parameters that should be measured in the future to validate the SWB intercropping model.

3.5.2 SWB Soil Water Component Outputs

Considering the SW balance flows from a productive and unproductive perspective across very different seasons provides an insight into the SW balance advantages and disadvantages of the various cropping systems. When considering the productive losses of transpiration, PaCr transpired proportionately at 7% and 4% more than CM in 2013-14 and 2015 respectively which implies that PaCr was more effective at transpiring more SW. These differences are less between PaCr and PM, amounting to 5% and 2%, also implying that a PM alone is already very efficient with water.

When considering the differences in ΔSW in 2013-14, there is a slight SW loss in CM of 2.5% whereas there was a SW retention of 5.4% and 11.3% for PM and PaCr. In 2015 there is a very significant drop in SW without significant drainage (<1%) of 15%, 23% and 20% of total SW balance for CM, PM and PaCr for the 2015 season. This implies that the crop relied heavily on SW reserves to transpire.

The unproductive losses of the SW balance include drainage, interception and evaporation. These losses amounted to 73%, 79% and 80% for CM, PM and PaCr in 2013-14 and 64%, 55% and 57% for CM, PM and PaCr in 2015. As expected, in 2013-14 there was more drainage due to bigger rainfall events thus drainage was the biggest loss factor in a wetter season representing 45%, 36% and 40% of the SW balance for the CM, PM and PaCr systems respectively. Consecutive rainfall events where over 100 mm fell on already saturated soils resulted in a large amount of SW draining beyond the boundaries of the soil profile. For PM and PaCr 5% and 8% less water was lost to drainage as compared to CM. This can be crucial if one considers that rainfall events are getting bigger and more sporadic with climate change (Murungweni, Van Wijk, Smaling, & Giller, 2016) and so it would be desired to have a system such as PaCr and PM that transpires more water right from the beginning of the season inducing a bigger SW deficit and thus capturing a greater proportion of precipitation infiltrating after large rain events. As mentioned, in 2015 the drainage was <1% for all treatments.

When considering the losses due to evaporation (which in this case includes canopy precipitation interception as this is ultimately evaporated to the atmosphere), this was much higher in PaCr and PM than expected. In 2013-14, this was 28%, 43% and 40% for CM, PM and PaCr systems respectively and in 2015 this was 64%, 54% and 56% for CM, PM and PaCr systems respectively. Hence the losses to the atmosphere were significantly higher in the drier 2015 season, particularly for CM. This was primarily due to high evaporative losses because of lower fractional radiation interception from lower growth. The losses in both seasons to precipitation interception in PM and PaCr was more than double that of CM which was surprising. This negating any gains in reduced evaporation by PM and PaCr.

In summary, CM lost 8% less water in 2015 versus 2013-14, whereas PM and PaCr lost 24% and 23% less water. This can be attributed to no drainage in 2015. The key element in these comparisons is that in a drier season loss to the atmosphere by evaporation is negated by the losses to drainage in the wetter season.

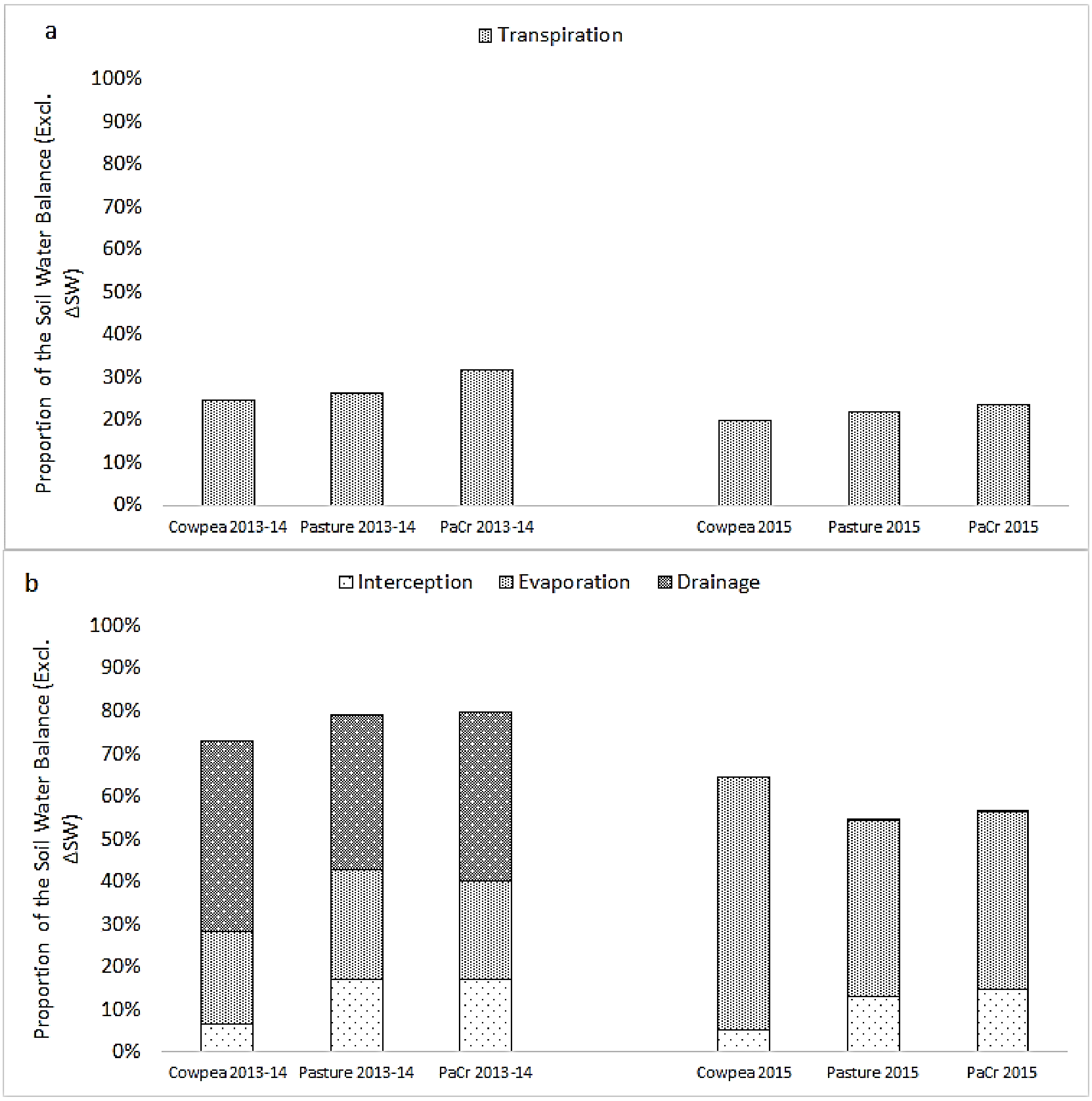


Figure 3-6 Comparisons between cropping systems and seasons of proportional productive losses (a) and unproductive losses (b) of the soil water balance dynamics (excluding ΔSW).

3.6 Conclusion

The goodness of fit of the observed versus the simulated data is very encouraging when considered in the context of the very extreme seasons, a first attempt at adapting the model to intercropping and making significant assumptions such as radiation playing a limited role in the yield results. This simplistic adaptation to integrating two crops into the framework that was designed for one crop seemingly captures the core interactions between the two crops on a SW basis. The SWB adaptation is also a first attempt at making the SWB model an intercropping model which, when compared to other model such as STICS where the standardised RMSE is 33% for above ground dry matter, is comparable to the SWB results. The primary objective of the adapted SWB and comparison to the observed data was to explore how the SW dynamics would alter the water balance in the varying cropping systems. The interesting and crucially unexpected results, such as the pivotal influence of precipitation interception by the canopy observed in the simulated data means that adaptation to SWB has served its purpose of filling in the gaps in the SW dynamics. This gives crucial guidance and lays a very good framework for the next stage of potential field data collection and validation for the next intercropping version of SWB. To summarise, the adaptations to the SWB model sufficiently captures the trends and scales to justify using the adapted version to explore and extrapolate the dynamics of PaCr over a longer time scale and in various climates and soils.

3.7 References

Adiku, S. G. K., Carberry, P. S., Rose, C. W., McCown, R. L., & and Braddock, R. (1995). A maize (Zea mays)-cowpea (Vigna unguiculata) intercrop model. *Ecophysiology of Tropical Intercropping*, pp. 397–406.

Allen, R. G. (1998). FAO Irrigation and Drainage Paper Crop by. *Irrigation and Drainage*, *300*(56), 300.

Annandale, J. G., Benadé, N., Jovanovic, N. Z., & Du Sautoy, N. (1999). Facilitating irrigation scheduling by means of the soil water balance model. In *WRC Report No. 753/1/99*.

Annandale, J. G., Jovanovic, N. Z., Campbell, G. S., Du Sautoy, N., & Benadé, N. (2003). A two-dimensional water balance model for micro-irrigated hedgerow tree crops. *Irrigation Science*, *22*(3–4), 157–170.

Anyia, A. O., & Herzog, H. (2004). Water-use efficiency, leaf area and leaf gas exchange of cowpeas under mid-season drought. *European Journal of Agronomy*, *20*(4), 327–339.

Balasubramanian, A. (2014). *Agro-Ecological Zones*. (March).

Barrett-Lennard, P., Dolling, P., & Ferris, D. (2010). *The advantages and disadvantages of pasture cropping in Farmer ' s perceptions*.

Baumann, D. T., Bastiaans, L., Goudriaan, J., Van Laar, H. H., & Kropff, M. J. (2002). Analysing crop yield and plant quality in an intercropping system using an eco-physiological model for interplant competition. *Agricultural Systems*, *73*(2), 173–203.

Bedoussac, L., & Justes, E. (2011). A comparison of commonly used indices for evaluating species interactions and intercrop efficiency: Application to durum wheat-winter pea intercrops. *Field Crops Research*, *124*(1), 25–36.

Beletse, Y. G. (2006). *Modelling the soil water and salt balance of planted pastures irrigated with sodium sulphate rich mine effluent*. University of Pretoria.

Bertness, M. D., & Callaway, R. (1994). Positive interactions in communities. *Trends in Ecology and Evolution*, *9*(5), 187–191.

Brisson, N., Bussiere, F., Ozier-Lafontaine, H., Tournebize, R., & Sinoquet, H. (2004). Adaptation of the crop model STICS to intercropping. Theoretical basis and parameterisation N. *Agronomie*, *24*(24), 409–421.

Bruce, S. E., Howden, S. M., Graham, S., Seis, C., Ash, J., & Nicholls, A. O. (2005). *Pasture-cropping: Effect on biomass, total cover, soil water and nitrogen*. (Chittelborough 1992), 141–147.

Caldwell, R. M., & Hansen., J. W. (1993). Simulation of multiple cropping systems with CropSys. In *Systems approaches for agricultural development 2* (p. 397–412.). Springer Science & Business Media.

Campbell G. S., & Diaz, R. (1988). *Simplified Soil-Water Balance Models to Predict Crop Transpiration* (F. R. Bidinger & C. Johansen, Eds.). Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics.

Carberry, P. S., McCown, R. L., Muchow, R. C., Dimes, J. P., Probert, M. E., Poulton, P. L., & Dalgliesh, N. P. (1996). Simulation of a legume ley farming system in northern Australia using the Agricultural Production Systems Simulator. *Australian Journal of Experimental Agriculture*, *36*(8), 1037–1048.

Casper, B. B., & Jackson, R. B. (1997). Plant competition underground. *Annu. Rev. Ecol. Syst.*, *28*, 545–570.

Chaves, M. M., Pereira, J. S., Maroco, J., Rodrigues, M. L., Ricardo, C. P. P., Osório, M. L., … Pinheiro, C. (2002). How plants cope with water stress in the field. Photosynthesis and growth. *Annals of Botany*, *89*(SPEC. ISS.), 907–916.

Chikowo, R., Corbeels, M., Tittonell, P., Vanlauwe, B., Whitbread, A., & Giller, K. E. (2008). Aggregating field-scale knowledge into farm-scale models of African smallholder systems: Summary functions to simulate crop production using APSIM. *Agricultural Systems*, *97*(3), 151–166.

Christine Jones. (1999). Cropping native pasture and conserving biodiversity: a potential technique. In *Conservation and Production in Grassy Landscapes.* Clare, South Australia.

Colom, M. R., & Vazzana, C. (2001). Drought stress effects on three cultivars of Eragrostis curvula: Photosynthesis and water relations. *Plant Growth Regulation*, *34*(2), 195–202.

Conway, G., & Toenniessen, G. (1999). Feeding the world in the twenty-first century. *Nature*, *402*(6761 Suppl), C55–C58.

Corbett, E. S., Crouse, & Robert P. (1968). Rainfall interception by annual grass and chaparral . . . losses compared. *U.S. Forest Serv. Res. Paper PSW*.

Coucheney, E., Buis, S., Launay, M., Constantin, J., Mary, B., & Cort, D. (2015). Environmental Modelling & Software Accuracy , robustness and behavior of the STICS soil e crop model for plant , water and nitrogen outputs : Evaluation over a wide range of agro-environmental conditions in France. *Environmental Modelling & Software*, *64*(64), 177–190.

Craig, P. R., Badgery, W., Millar, G., & Moore, A. (2015). Achieving modelling of pasture-cropping systems with APSIM and GRAZPLAN. *Proceedings of the 17th ASA Conference - Building Productive, Diverse and Sustainable Landscapes*, (September), 2013–2016.

Descheemaeker, K., Amede, T., & Haileslassie, A. (2009). *Livestock and water interactions in mixed crop-livestock farming systems of sub-Saharan Africa: interventions for improved productivity*.

Finlayson, J. D., Lawes, R. A., Metcalf, T., Robertson, M. J., Ferris, D., & Ewing, M. A. (2012). A bio-economic evaluation of the profitability of adopting subtropical grasses and pasture-cropping on crop-livestock farms. *Agricultural Systems*, *106*(1), 102–112.

Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., & Holling, C. S. (2004). Regime Shifts, Resilience, and Biodiversity in Ecosystem Management. *Annual Review of Ecology, Evolution, and Systematics*, *35*(2004), 557–581.

Fukai, S., & Trenbath, B. R. (1993). Processes determining intercrop productivity and yields of component crops. *Field Crops Research*, *34*(3–4), 247–271.

Glatzel, K., Conway, G., Alpert, E., & Brittain, S. (2014). *No ordinary matter: Conserving, restoring and enhancing Africa's soils*. (December), 40.

Glover, J., Duggan, J., & Jackson, L. (2010). *A novel perennial pasture and winter wheat conservation agriculture intercrop system for central USA*. 1–4.

Goldberg, D. E. (1996). Competitive ability: Definitions, contingency and correlated traits. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *351*(1345), 1377–1385.

Hacker, R. B., Robertson, M. J., Price, R. J., & Bowman, A. M. (2009). Evolution of mixed farming systems for the delivery of triple bottom line outcomes: A synthesis of the Grain & Graze program. *Animal Production Science*, *49*(10), 966–974.

Hatfield, J. L., Sauer, T. J., & Prueger, J. H. (2001). Managing Soils to Achieve Greater Water Use Efficiency : A Review Managing Soils to Achieve Greater Water Use Efficiency : A Review. *Agronomy Journal*, *93*, 271–280.

Heuzé, V., Tran, G., Giger-Reverdin, S., Renaudeau, D., Bastianelli, D., & Lebas, F. (2015). Cowpea (Vignia unguiculata) forage. Feedipedia, a programme by INRA, CIRAD, AFZ and FAO. Retrieved from Feedipedia website:

Holmgren, M., Scheffer, M., & Huston, M. A. (2009). The Interplay of Facilitation and Competition in Plant Communities. *Ecology*, *78*(7), 1966–1975.

Huth, N. I., Bristow, K. L., & Verburg, K. (2012). Swim3: Model use, calibration, and validation. *American Society of Agricultural and Biological Engineers*, *55*(4), 1303–1313.

Johnston, W. H., Koen, T. B., & Shoemark, V. F. (2002). Water use, competition, and a temperate-zone C4 grass (Eragrostis curvula (Schrad.) Nees. complex) cv. Consol. *Australian Journal of Agricultural Research*, *53*(6), 715–728.

Jones, H. G. (1998). Stomatal control of photosynthesis and transpiration. *J Exp Bot*, *49*(July 1997), 387–398.

Kabirizi, J., Ziiwa, E., Mugerwa, S., Ndikumana, J., & Nanyennya, W. (2013). *Dry season forages for improving dairy production in smallholder systems in Uganda*. *1*, 212–215.

Keating, B. A., Carberry, P. S., Hammer, G. L., & Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N., Meinke, H., Hochman, Z. and McLean, G. (2003). *An overview of APSIM, a model designed for farming systems simulation* (pp. 267–288). pp. 267–288.

Kiniry, J. R., Williams, J. ., Gassman, P. ., & Debaeke, P. (1992). A General, Process-Oriented Model for Two Competing Plant Species. *Transactions of the ASAE*, *35*(3), 801.

Kirkham, M. B. (2005). Water-Use Efficiency. *Encyclopedia of Soils in the Environment*, 315–322.

Knörzer, H., Graeff-Hönninger, S., Müller, B. U., Piepho, H.-P., & Claupein, W. (2010). A Modeling Approach to Simulate Effects of Intercropping and Interspecific Competition in Arable Crops. *International Journal of Information Systems and Social Change*, *1*(4), 44–65.

Lawes, R. A., Ward, P. R., & Ferris, D. (2014). Pasture cropping with C4 grasses in a barley-lupin rotation can increase production. *Crop and Pasture Science*, *65*(10), 1002–1015.

Lightfoot, C. W. F., Dear, K. B. G., & Mead, R. (1987). *lIntercropping sorghum with cowpea in dryland farming systems in Borswana. II. Comparative stability of alternative cropping systems*. *23*, 435–442.

Lightfoot, C. W. F., & Tayler, R. S. (1987). Intercropping sorghum with cowpea in dryland farming systems in Botswana. I. Field experiments and relative advantages of intercropping. *Experimental Agriculture*, *23*(04), 425–434.

Liu Guobin, L., Kemp, D. R., & Liu, G. B. (1992). Water stress affects the productivity, growth components, competitiveness and water relations of phalaris and white clover growing in a mixed pasture. *Australian Journal of Agricultural Research*, *43*(3), 659–672.

Lodge, G. M., & Mccormick, L. H. (2006). Pasture cropping in northern NSW – do the numbers for plant available water stack up? *Proceedings of the 25th Annual Conference of The Grassland Society of NSW*, (1), 166–168.

Lowenberg-DeBoer, J., Krause, M., Deuson, R., & Reddy, K. C. (1991). Simulation of yield distributions in millet-cowpea intercropping. *Agricultural Systems*, *36*(4), 471–487.

Maestre, F. T., Valladares, F., & Reynolds, J. F. (2005). Is the change of plant-plant interactions with abiotic stress predictable? A meta-analysis of field results in arid environments. *Journal of Ecology*, *93*(4), 748–757.

Marais, D., Rethman, N., & Annandale, J. (2006). Dry matter yield and water use efficiency of five perennial subtropical grasses at four levels of water availability. *African Journal of Range and*

Forage Science, *23*(3), 165–169.

Millar, G. D., & Badgery, W. B. (2009). Pasture cropping: A new approach to integrate crop and livestock farming systems. *Animal Production Science*, *49*(10), 777–787.

Morris, R. A., & Garrity, D. P. (1993a). Resource capture and utilization in intercropping; non-nitrogen nutrients. *Field Crops Research*, *34*(3–4), 319–334.

Morris, R. A., & Garrity, D. P. (1993b). Resource capture and utilization in intercropping: water. *Field Crops Research*, *34*(3), 303–317.

Mureithi, S. M., Verdoodt, A., Njoka, J. T., Gachene, C. K. K., & Ranst, E. Van. (2015). *Benefits Derived From Rehabilitating a Degraded Semi-Arid Rangeland in Communal Enclosures , Kenya*.

Murungweni, C., Van Wijk, M. T., Smaling, E. M. A., & Giller, K. E. (2016). Climate-smart crop production in semi-arid areas through increased knowledge of varieties, environment and management factors. *Nutrient Cycling in Agroecosystems*, *105*(3), 183–197.

Natarajan, M., & Willey, R. W. (1986). *Field Crops Research The effects of water stress on yield advantages of intercropping systems*. *13*, 117–131.

Njoka-Njiru, E. N., Njarui, M. G., Abdulrazak, S. A., & Mureithi, J. G. (2006). Effect of intercropping herbaceous legumes with napier grass on dry matter yield and nutritive value of the feedstuffs in semi-arid region of Eastern Kenya. *Agricultura Tropica et Subtropica*, *39*(4), 255–267.

Nkonya, E., Gerber, N., von Braun, J., De Pinto, A., & Braun, J. Von. (2011). Economics Of Land Degradation. *IFRI Issue Briefs*, *68*(September), 1–7.

O’Callaghan, J. R., Maende, C., & Wyseure, G. C. L. (1994). Modelling the intercropping of maize and beans in Kenya. *Computers and Electronics in Agriculture*, *11*(4), 351–365.

Ofori, F., & Stern, W. R. (1987). Cereal–Legume Intercropping Systems. *Advances in Agronomy*, *41*(C), 41–90.

Orin Ray Clark. (1940). Interception of Rainfall by Prairie Grasses, Weeds, and Certain Crop Plants. *Ecological Society of America*, *10*(2), 243–277.

Ozier-Lafontaine, H. F., Lafolie, F., Bruckler, L., Tournebize, A., & Mollier, A. (1998). Modelling competition for water in intercrops: theory and comparison with field experiments. *Plant and Soil*, *204*, 183–201.

Ozier-Lafontaine, H. F., Lafolie, F., Bruckler, L., Tournebize, A., & Mollier, A. (1999). Modeling soil-root water transport and competition for single and mixed crops. *Plant and Soil*, *210*, 127–143.

Rees, D. J. (1986a). Crop growth , development and yield in semi- arid conditions in botswana . ii . The effects of intercropping sorghum bicolor with vigna unguiculata. *Experimental Agriculture*, *22*, 169–177.

Rees, D. J. (1986b). The effects of population density and intercropping with cowpea on the water use and growth of sorghum in semi-arid conditions in Botswana. *Agricultural and Forest Meteorology*, *37*(4), 293–308.

Rockström, J. (2000). Water Resources Management in Smallholder Farms in Eastern and Southern Africa : an Overview. *Phys. Chem. Earth (B)*, *25*(3), 275–283.

Rockström, J., Barron, J., & Fox, P. (2002). Rainwater management for increased productivity among small-holder farmers in drought prone environments. *Physics and Chemistry of the Earth*, *27*(11–22), 949–959.

Rockström, J., Barron, J., & Fox, P. (2003). Water Productivity in Rain-fed Agriculture: Challenges and Opportunities for Smallholder Farmers in Drought-prone Tropical Agroecosystems. *Water Productivity in Agriculture: Limits and Opportunities for Improvement*, 145–162.

Schultze-Kraft, R., Rao, I. M., Peters, M., Clements, R. J., Bai, C., & Liu, G. (2018). Tropical forage legumes for environmental benefits: An overview. *Tropical Grasslands-Forrajes Tropicales*, *6*(1), 1.

Seis, C. (2006). Pasture cropping as a means to managing land. *Australian Organic Journal*, *Winter 200*(66), 42–43.

Sekhon, H. S., Singh, G., Sharma, P., & Bains, T. S. (2010). *Water Use Efficiency Under Stress Environments*.

Sengul, S. (2003). Performance of some forage grasses or legumes and their mixtures under dry land conditions. *European Journal of Agronomy*, *19*(3), 401–409.

Shepherd, K. D., Vanlauwe, B., Tittonell, P., Giller, K. E., & Leffelaar, P. A. (2005). Exploring diversity in soil fertility management of smallholder farms in western Kenya. *Agriculture, Ecosystems & Environment*, *110*(3–4), 166–184.

Silburn, D. M., Robinson, J. B., & Freebairn, D. M. (2007). Why restore marginal cropland to permanent pasture? Land resource and environmental issues. *Tropical Grasslands*, *41*(3), 139–

153.

Sinclair, T. R., Tanner, C. B., & Bennett, J. M. (1984). Water-Use Efficiency in Crop Production. *BioScience*, *34*(1), 36–40.

Snaydon R, W., & Satorre E, H. (1989). Bivariate diagrams for plant competition data modifications and interpretation. *Journal of Applied Ecology*, *26*(3), 1043–1057.

Snyman, H. A. (1990). *The influence of range condition on the hydrological characteristics in a semi-arid rangeland*. (106), 93–94.

Snyman, H. A. (1994). Evapotranspiration, water-use efficiency and quality of six dryland planted pasture species and natural vegetation, in a semi-arid rangeland. *African Journal of Range and Forage Science*, *11*(3), 82–88.

Snyman, H. A. (1999). Quantification of the soil-water balance under different veld condition classes in a semi-arid climate. *African Journal of Range Forage Science*, *16*(2), 108.

Snyman, H. A. (2005). Rangeland degradation in a semi-arid South Africa - I: Influence on seasonal root distribution, root/shoot ratios and water-use efficiency. *Journal of Arid Environments*, *60*(3), 457–481.

Valbuena, D., Erenstein, O., Homann-Kee Tui, S., Abdoulaye, T., Claessens, L., Duncan, A. J., … van Wijk, M. T. (2012). Conservation Agriculture in mixed crop-livestock systems: Scoping crop residue trade-offs in Sub-Saharan Africa and South Asia. *Field Crops Research*, *132*, 175–184.

Van Duivenbooden, N., Pala, M., Studer, C., Bielders, C. L., & Beukes, D. J. (2000). Cropping systems and crop complementarity in dryland agriculture to increase soil water use efficiency: a review. *NJAS - Wageningen Journal of Life Sciences*, *48*(3), 213–236.

Vandermeer, J., & Schultz, B. (1990). *Agroecology* (S. R. Gliessman, Ed.).

Vohland, K., & Barry, B. (2009). A review of in situ rainwater harvesting (RWH) practices modifying landscape functions in African drylands. *Agriculture, Ecosystems and Environment*, *131*(3–4), 119–127.

Wahua, T. A. T., Babalola, O., & Aken’ova, M. E. (1981). Intercropping morphologically different types of maize with cowpeas: LER and growth attributes of associated cowpeas. *Experimental Agriculture*, *17*(4), 407–413.

Ward P. R., Lawes, R. A., & Ferris, D. (2014). Soil-water dynamics in a pasture-cropping system. *Crop* *and Pasture Science*, *65*(10), 1016–1021.

White, C. (2012). *Pasture Cropping*. *42*(7).

Willey, R. W. (1990). Resource use in intercropping systems. *Agricultural Water Management*, *17*(1), 215–231.

Winterbottom, R., Reij, C., Garrity, D., Glover, J., Hellums, D., McGahuey, M., & Scherr, S. (2013). Improving land and water management. *World Resources Institute*, (October), 1–44.

Yaacob, O., & Blair, G. J. (1981). Effect of legume cropping and organic matter accumulation on the infiltration rate and structural stability of a granite soil under a simulated tropical environment. *Plant and Soil*, *60*(1), 11–20.

4. Assessing Pasture Cropping Under Different Aridity Levels and Soil Types Using Long Term Soil Water Balance Simulations.

R N Orford[1], N Benade[3], M van der Laan[2], J G Annandale[2], F Asch[1].

[1] Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg-Institute), University of Hohenheim: Crop Water Stress Management in the Tropics and Subtropics, Hohenheim University. Garbenstr. 13, 70599 Stuttgart, Germany,

[2] The institute of Plant Production and Agroecology in the Tropics and Subtropics, Department of Plant and Soil Sciences, University of Pretoria, Private Bag X20 Hatfield, Pretoria 0028.

[3] NB Systems. NB Systems cc, Sinoville, Pretoria, South Africa, E-mail: nicob@mweb.co.za

4.1 Introduction

The inherent challenge and distinctive feature of small holder farming systems in most of sub-Saharan Africa (SSA) is that it is highly unpredictable. The variable nature of not only socio-economic conditions but also the bio-physical (particularly soil and climatic) dynamics (Chikowo et al., 2008; J Rockström, Barron, & Fox, 2003; Shepherd, Vanlauwe, Tittonell, Giller, & Leffelaar, 2005) create this challenge. Rockström (2003) demands that as such, long term simulations must be carried out. Such systems are plagued by high intensity rainfall events with large spatial and temporal variability, with coefficients of variation ranging from 20-40%, increasing as seasonal rainfall averages decrease. With such dry spells, the water holding capacity of a soil plays a major role in the degree of stress experienced by a crop in the rain free days (Johan Rockström, 2000). These two factors are major contributors to the dynamic and unpredictable nature of agriculture which increases the difficulty of decision making in the short and long term. Furthermore, the high degree of variability in these systems can disguise the true long-term dynamics of them, resulting in conclusions that are mistaken in the context of long-term sustainable decision making. This is made even more complicated when more than one crop is considered. The aim of this paper is to identify through long term soil water balance (SWB) simulations whether pasture cropping (PaCr) is a potential cropping system that can improve water use efficiency and reduce the crop failure risk of crop production in SSA. Furthermore, it also exposes the strengths and weakness of the adaptations to SWB in a more complete framework of data.

Ultimately the results of such simulations provide more guidance to policy makers and researchers in order to focus their efforts on most likely locations to increase the return on investment when it comes to implementing policy and research decisions in the future.

The objective was to identify and quantify under which soil textures and degree of aridity pasture cropping (PaCr) yields the most dry-matter and is most resilient relative to its respective cowpea and pasture monocrop equivalent. Furthermore, what is the long-term degree of intercrop competition for water in PaCr under varying degrees of aridity and soil texture and what SW dynamics underpin these competitive outcomes? This will allow for a preliminary assessment to determine where PaCr would most likely be successful in the context of soil type and aridity and what the outcomes are with respect to competition for water in such a system. To achieve this, the adapted soil water balance (SWB) model was run over 14-year simulations specifically looking at yield, water balance dynamics and SW driven competition.

The hypothesis is that PaCr will get a higher yield in the semi-arid and dry sub-humid aridity categories, due to (1) deep drainage being eliminated; (2) that the evaporation being reduced thus increasing SW availability for transpiration and that (3) similarly competition will be offset by the complementarity offered by the deep roots of the pasture, thus increasing the overall DM yield. All these factors will provide a greater advantage in drier conditions where water is a limited resource. These factors should also be most successful on sandy soils where deeper roots of pasture in PaCr will enable water uptake from deeper soil strata when the limited water holding capacity is used up in the top soil. Finally (4) we assume the cropping system resilience will be increased in PaCr versus cowpea monocrop due to the two crops offering diversification against the varying climatic conditions. Different crop attributes such as different root depth, will enable growth in more conditions relative to a cropping system with only the attributes of one crop.

4.2 Methods and Materials

The modified SWB model (Orford *et al*, 2018) was set to a standardised configuration used to simulate measured results from 2013-14 and 2015 field trials (See

Table 4-1) with *Vigna unguiculata* and *Eragrostis curvula* run over three different soil textures (Clay, Clay-Loam, Sand) (see Table 4-3) and three different climates chosen primarily for different annual rainfall (see Table 4-2). All conditions apart from climate, soil type and differences observed between the cowpea in the 2013-2014 and 2015 field trials, were kept the same over the 14-season simulations All simulations commenced on 23 October. The yield results were confined to dry matter analysis due to the limited confidence in the grain yield results of the 2015 trials. There was also an assumption that DM in such a system would give a more comparative metric as the pasture is generally grown for DM, and hence the cowpea would be assessed on the same metric.

Table 4-1 Showing the parameters used to run the long-term simulations for *Vigna unguiculata* and *Eragrostis curvula*.

Parameter	Cowpea Monocrop (2013-14)	Cowpea PaCr (2013-14)	*E. curvula* (2013-14)
Canopy extinction coefficient for total solar radiation K_{s*}	0.59	0.59	0.45
Dry matter/evapotranspiration ratio corrected for vapour pressure deficit DWR (Pa)*	3.5	3.5	4
Radiation conversion efficiency ($g \cdot MJ^{-1}$) *	0.0013	0.0013	0.0009
Base temperature (°C) *	10	10	10
Optimum temperature (°C) *	25	25	15
Cut-off temperature (°C) *	30	30	25
Emergence day degrees* (d °C) *	43	43	0[ǂ]
Day degrees at end of vegetative growth (d °C) *	2000	2000	1500
Day degrees for maturity (d °C) *	2000	2000	1500
Transition period day degrees (d °C)*	200	200	10
Day degrees for leaf senescence (d °C)*	1190	1190	700
Maximum crop height Hmax (m)*	0.55	0.55	0.5
Maximum root depth Rdmax (m)*	0.6	0.6	0.7
Specific leaf area SLA ($m^2 \cdot kg^{-1}$) [◊]	17.3	17.3	8.2
Leaf-stem partition parameter p ($m^2 \cdot kg^{-1}$) [◊]	1	1	0.3
Canopy Storage (mm)**	2[&]	2[&]	6[&]
TDM at emergence (kg/m^2) *	0.0019	0.0019	0.04
Root growth rate ($m^2 \cdot kg^{-0.5}$) *	5	5	20

**(Annandale et al., 1999; Beletse, 2006)*

*** Calculated and includes mulch in the pasture-based systems.*

◊ *Measured during the trial.*

ǂ *The Emergence day degrees (d °C) for E. curvula was set to zero as the crop is already established.*

& *(Corbett et al., 1968; Orin Ray Clark, 1940)*

Table 4-2 Location (Longitude; Latitude) and climate parameters of the three different locations used for the simulations. Coefficient of Variation (CV) for precipitation.

Rainfall type	Location	Longitude	Latitude	Precipitation (mm)	CV Precipitation	Et_o (mm)	Tmax (◦C)	Tmin (◦C)
High	Mtunzini	31.7	-28.93	1104	16%	4.17	26.93	16.15
Medium	Pretoria	28.23	-25.7	732	25%	4.43	24.54	10.67
Low	Tshabong	22.41	-26.02	319	80%	5.75	29.03	10.88

Pretoria was also chosen as a reference climate related to the Hatfield Research Farm where the trials were carried out in 2013-2014 and 2015. Two different regions were selected primarily for their different rainfall amounts and variation (see coefficient of variation in Table 4-2). They were also selected for their more sub-tropical latitudes.

Table 4-3 The various soil textured defined by their different soil available water thresholds of field capacity (FC) and wilting point (WP) used for the simulations.

	FC (%)	WP (%)	Total Available Water (%)
Clay-Loam	35	22	13%
Heavy Clay	45	34	11%
Sandy	15	7	8%

The various soil types were defined to provide an adequate range of different soil available water (SAW). These were defined by thresholds of field capacity (FC) and wilting point (WP). The FC and WP values were derived from the soil texture triangle and then calculated based on the texture calculator used in SWB model:

$$\boldsymbol{FC} = \mathbf{0.0037} \times (\boldsymbol{Silt}\,\% + \boldsymbol{Clay}\,\%) + \mathbf{0.139} \qquad \text{Eq. 18}$$

$$\boldsymbol{WP} = \mathbf{0.00385} \times (\boldsymbol{Silt}\,\% + \boldsymbol{Clay}\,\%) + \mathbf{0.013} \qquad \text{Eq. 19}$$

The simulations carried out were measured against the aridity index (AI). The AI is a numerical value that represents the level of dryness of a climate for a given season or at a given location. The index helps identify, locate or delimit the regions that suffer from deficit of water in crop land and is linked to agroecological zones (Balasubramanian, 2014) and is considered here as an ideal index for simulations where SW is the limiting factor. This parameter not only includes rainfall but also evapotranspiration demand which is a crucial parameter in defining water use by crops. Essentially there are geographical locations with 14 seasons of 90 days, with each season categorised into different AI values for more comparative reference.

The AI is calculated as:

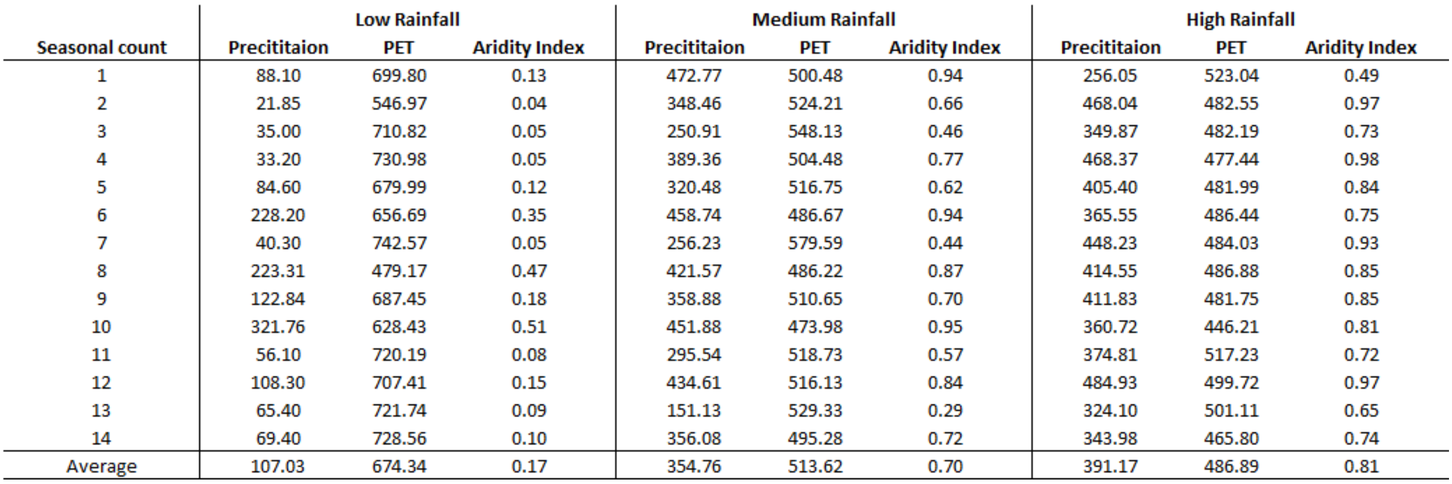
$$\boldsymbol{AI = P/PET} \qquad \text{Eq. 20}$$

where PET is the seasonal potential evapotranspiration and P is the average seasonal precipitation. P and PET must be expressed in mm (Balasubramanian, 2014).

Table 4-4 Regional water balance defined by the aridity index.

Regional Water Balance	Aridity Index	Global Land Area
Hyper-Arid	AI<0.05	7.5%
Arid	0.05<AI<0.2	12.1%
Semi-Arid	0.2<AI<0.5	17.7%
Dry Sub-Humid	0.5<AI< 0.65	9.9%
Sub-Humid	AI>0.65	37%

Table 4-5 The precipitation over the simulated seasons of 90 days. The aridity index was used as an index which can be used to define various regional water balances (see Table 4-4).



	Low Rainfall			Medium Rainfall			High Rainfall		
Seasonal count	**Precititaion**	**PET**	**Aridity Index**	**Precititaion**	**PET**	**Aridity Index**	**Precititaion**	**PET**	**Aridity Index**
1	88.10	699.80	0.13	472.77	500.48	0.94	256.05	523.04	0.49
2	21.85	546.97	0.04	348.46	524.21	0.66	468.04	482.55	0.97
3	35.00	710.82	0.05	250.91	548.13	0.46	349.87	482.19	0.73
4	33.20	730.98	0.05	389.36	504.48	0.77	468.37	477.44	0.98
5	84.60	679.99	0.12	320.48	516.75	0.62	405.40	481.99	0.84
6	228.20	656.69	0.35	458.74	486.67	0.94	365.55	486.44	0.75
7	40.30	742.57	0.05	256.23	579.59	0.44	448.23	484.03	0.93
8	223.31	479.17	0.47	421.57	486.22	0.87	414.55	486.88	0.85
9	122.84	687.45	0.18	358.88	510.65	0.70	411.83	481.75	0.85
10	321.76	628.43	0.51	451.88	473.98	0.95	360.72	446.21	0.81
11	56.10	720.19	0.08	295.54	518.73	0.57	374.81	517.23	0.72
12	108.30	707.41	0.15	434.61	516.13	0.84	484.93	499.72	0.97
13	65.40	721.74	0.09	151.13	529.33	0.29	324.10	501.11	0.65
14	69.40	728.56	0.10	356.08	495.28	0.72	343.98	465.80	0.74
Average	107.03	674.34	0.17	354.76	513.62	0.70	391.17	486.89	0.81

4.3 Results

4.3.1 Yield

4.3.1.1 Overall Trends

The most expected result was that yields were higher with the increased rainfall of sub-humid conditions as seen in Figure 4-1. The highest yields in general were also achieved on sandy soils. Across all soil types, the pasture monocrop performed the best across all aridity categories except in the sub-humid category. Pasture performed significantly better in the arid category. The cowpea monocrop only performed marginally better than the pasture monocrop under sub-humid conditions. There was no significant difference between the different soil types, however clay soils did underperform, with cowpea, pasture and PaCr yielding 18%, 17% and 67% less respectively relative to clay-loam. Pasture and PaCr yielded 24%, 40% and 102% less on clay soils respectively compared to sand across all aridity categories. Sand outperformed clay-loam with cowpea, pasture and PaCr yielding 5%, 19% and 21% more respectively.

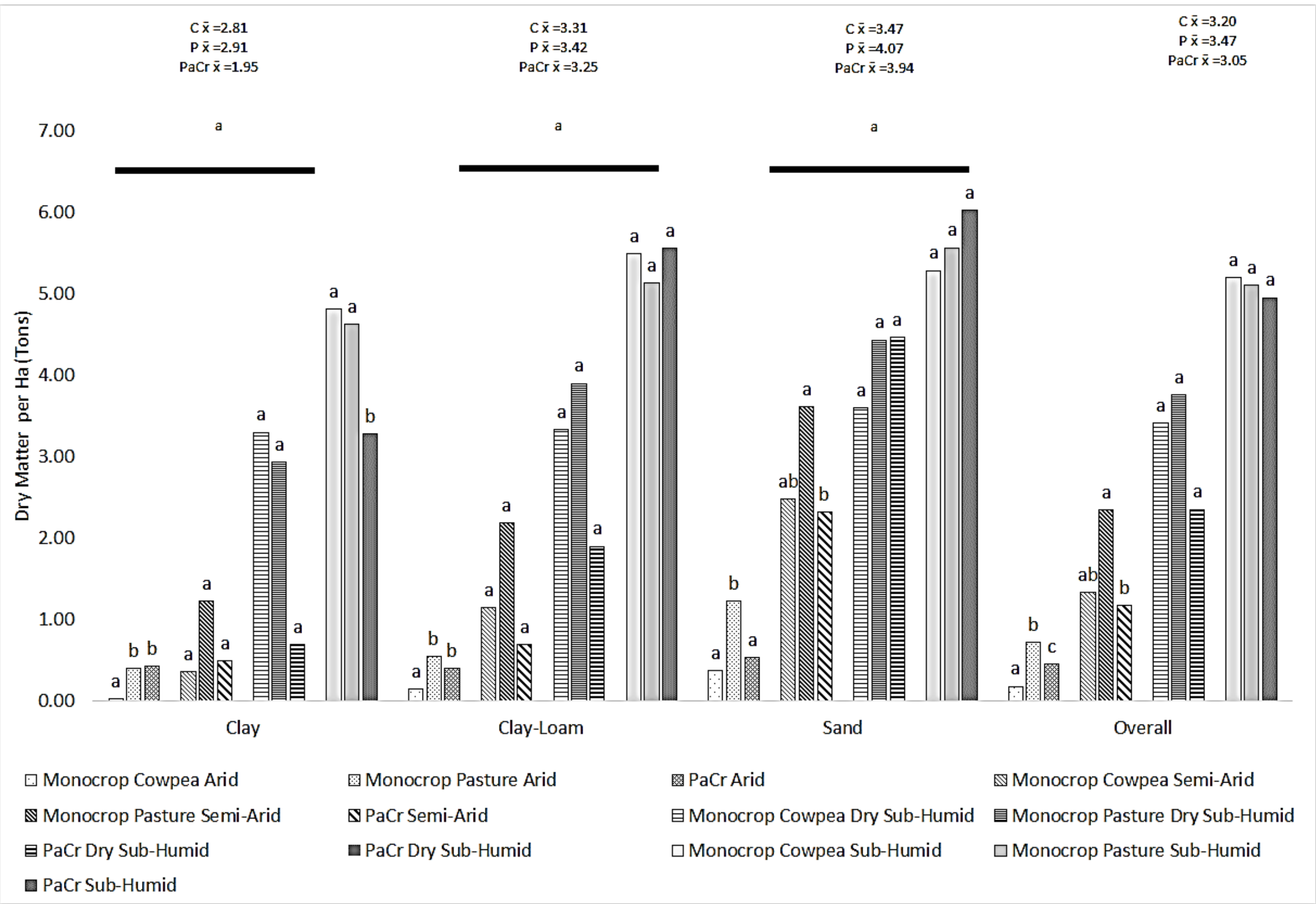


Figure 4-1 Graph showing the overall yield performance averaged for all seasons including crop failures across all soil types and aridity categories. Letters denote significance at P<0.05 specifically between the three different cropping systems in an aridity index category. x̄ denotes soil type average for a particular cropping system.

4.3.1.2 *Clay Soils*

On clay soils in general pasture had the highest yield as seen in average above the clay category columns, followed by cowpea and then PaCr. Under arid conditions PaCr yields slightly more DM with cowpea showing significantly lower yields. Under semi-arid conditions pasture yields were higher than cowpea and PaCr. Dry sub-humid conditions were the only category where cowpea performed better than the other cropping systems. In the sub-humid conditions PaCr yields stayed suppressed while cowpea and pasture yielded similar amounts. Crop failure occurred at 33% for cowpea, 29% for pasture and 26% for PaCr (see Figure 4-7). A very high coefficient of variation (CV) of 243% for the cowpea element in PaCr versus 109% for the pasture element also indicates a very unpredictable cowpea crop yield on clay soils.

4.3.1.3 Clay-Loam Soils

Overall, the pasture monocrop yields the most DM in clay-loam soils, then cowpea followed by PaCr. Pasture followed by PaCr performed significantly better than cowpea in arid conditions. Pasture followed by cowpea performed better than PaCr in semi-arid and dry sub-humid conditions. PaCr performs marginally better than pasture and cowpea in sub-humid conditions. Crop failure is reduced from 24% for cowpea in clay to 17% in clay-loam, 29% for pasture in clay to 14% for clay-loam and reverts to PaCr unexpectedly from 26% in clay to 31% (see Figure 4-7). There is a very noticeable reduction in the coefficient of variation (CV) for cowpea in clay from 243% to 123% in clay-loam revealing that the clay-loam conditions are more conducive to more consistent cowpea growth than clay in PaCr conditions.

4.3.1.4 Sandy Soils

Pasture performs overall marginally better on sandy soils, followed by PaCr and then cowpea. It also performs significantly better in arid and semi-arid conditions. Cowpea only yields slightly more than PaCr in the dry sub-humid conditions. PaCr yields more DM than both cowpea and pasture under sub-humid conditions. Crop failure drops to 5% for cowpea, 0% for pasture and 7% for PaCr (see Figure 4-7). There is a marked decreased covariance in all cropping systems in sand (see Figure 4-7).

4.3.1.5 *Protein Yields*

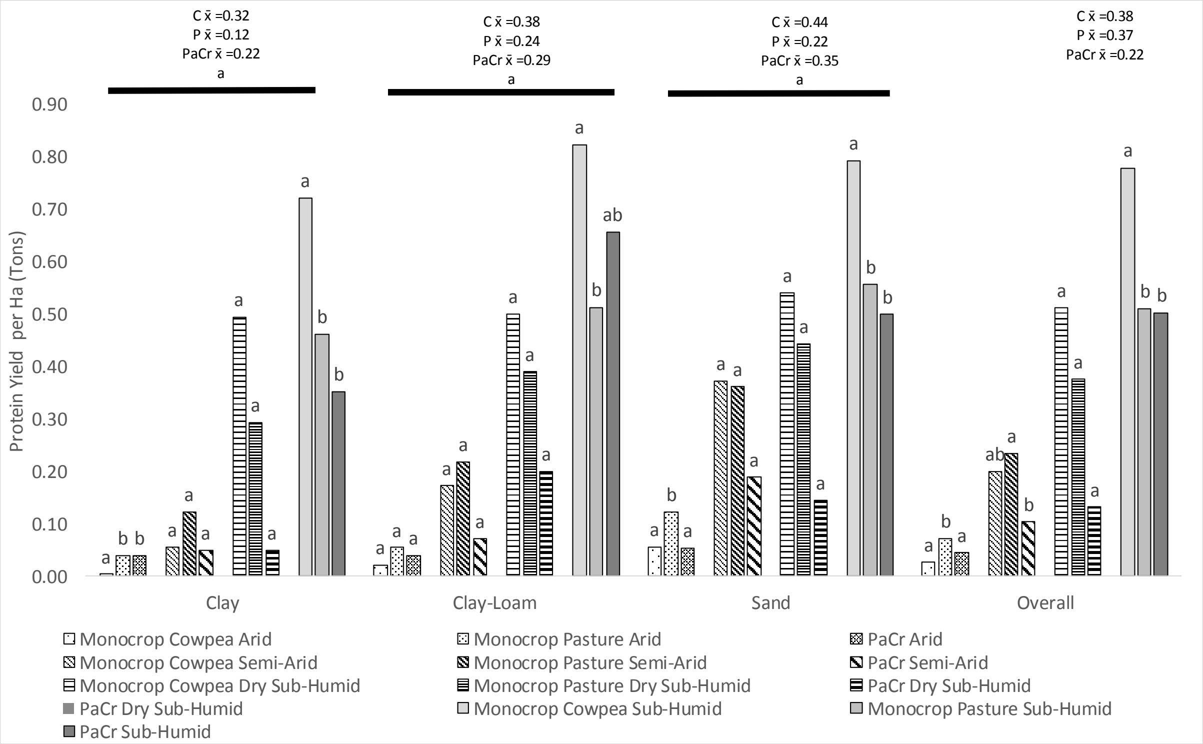


Figure 4-2 Graph showing the estimated overall protein yield performance averaged for all seasons including crop failures across all soil types and aridity categories. Letters denote significance at P<0.05. x̄ denotes soil type average for a particular cropping system.

When considering the protein yield against the AI using extrapolated values with values from literature (FAO, INRA, CIRA, www.feedopedia.org), the dynamics change. In all three soils cowpea protein yields are higher than all the other cropping systems in the dry sub-humid and sub-humid category. In clay soils PaCr and pasture yield more in arid conditions, while pasture yields more protein in the semi-arid conditions and cowpea is dominant in the dry sub-humid and sub-humid conditions. Under clay-loam soils pasture yields more in arid and semi-arid conditions, while cowpea dominates the dry sub-humid and sub-humid conditions. Sandy soils under arid and semi-arid conditions are dominated by pasture and in the humid and sub-humid conditions cowpea produces the most protein.

4.3.2 Soil Water Balance

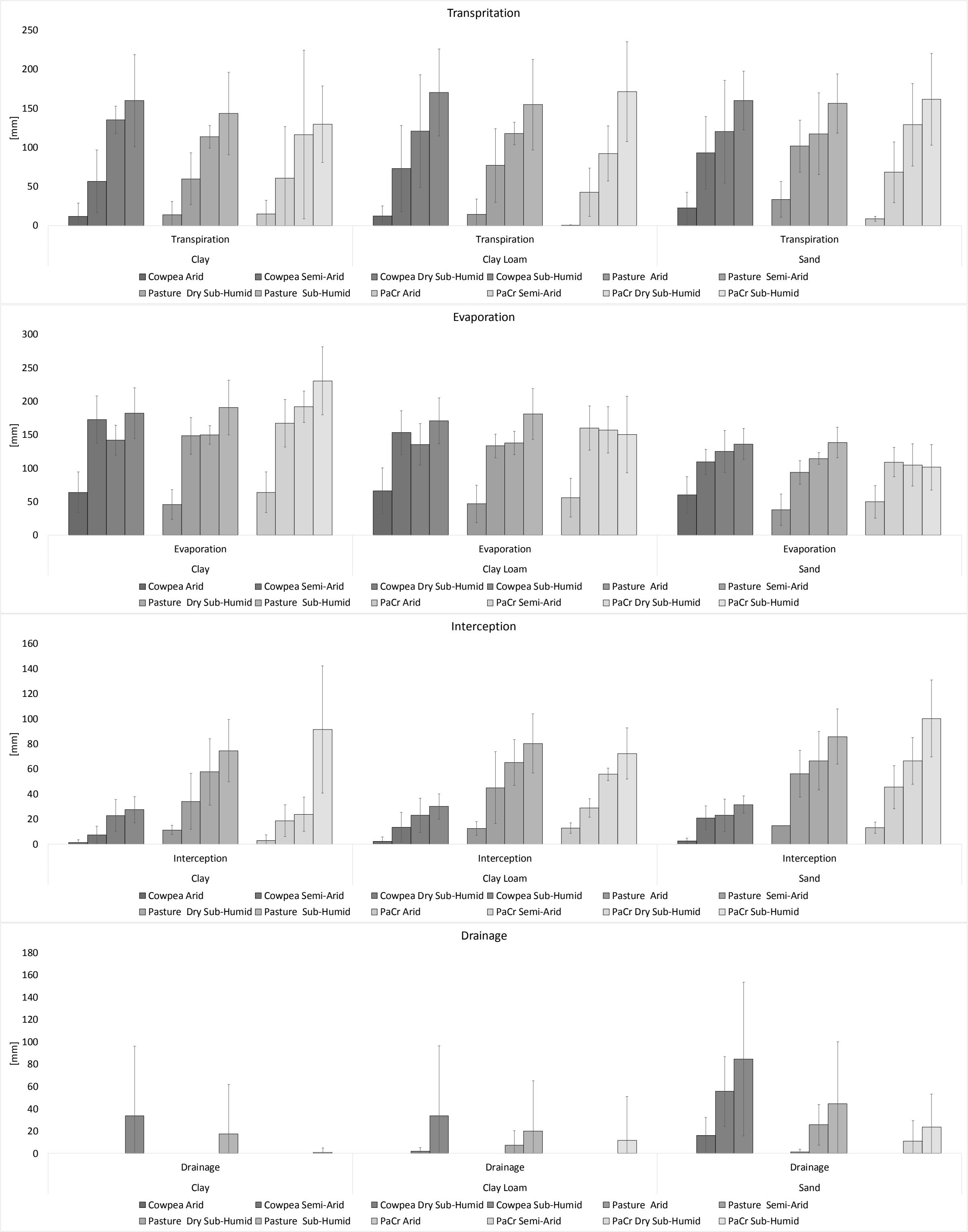


Figure 4-3 Distribution of a portion of the soil water balance across different soil types and cropping systems.

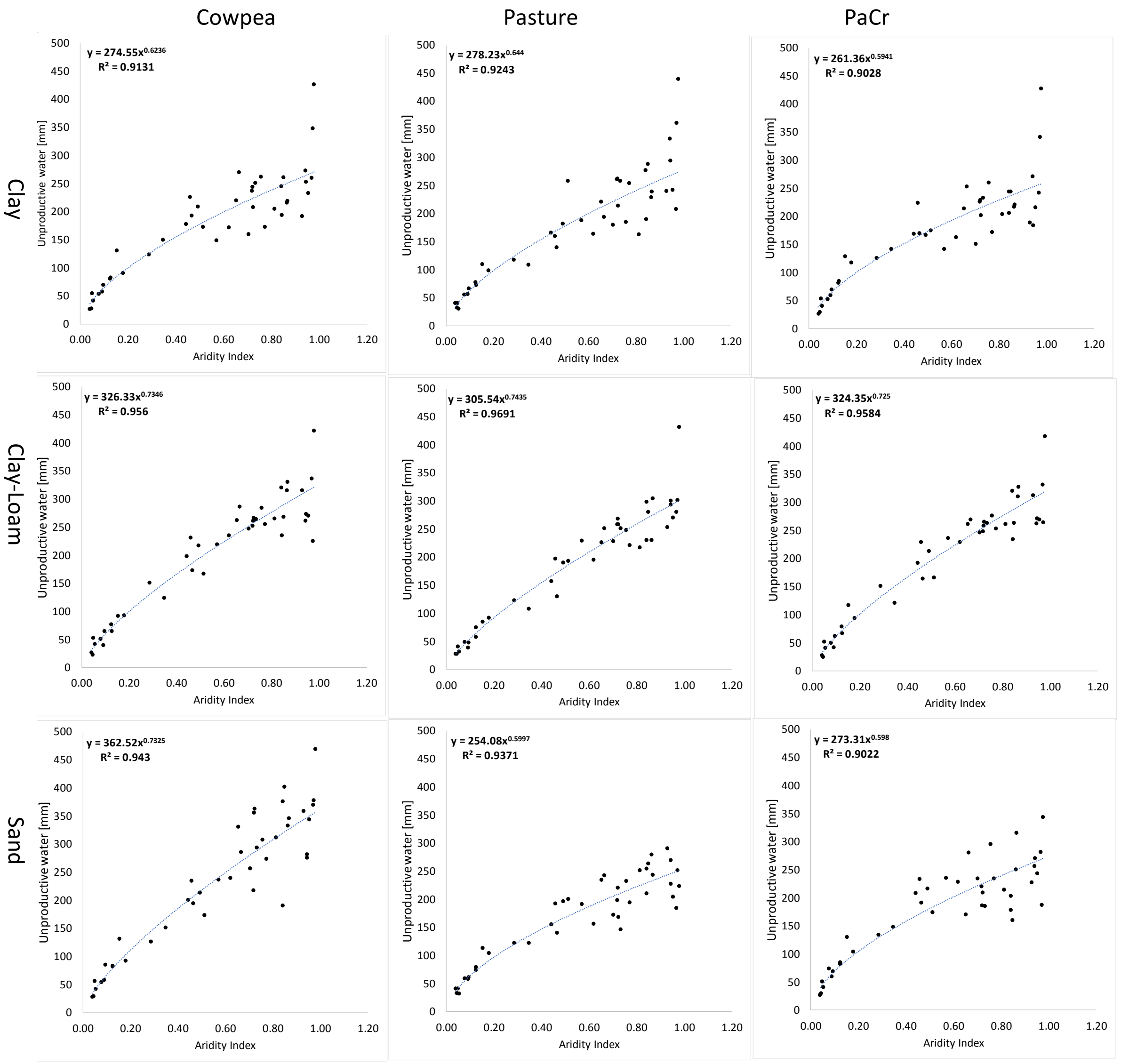


Figure 4-4 Scatter plots showing the range of unproductive water loss (evaporation, interception and deep drainage) for various soil types (clay, clay-loam, sand) and aridity index and cropping systems (cowpea monocrop is cowpea, *E. curvula* is pasture and pasture cropping is PaCr).

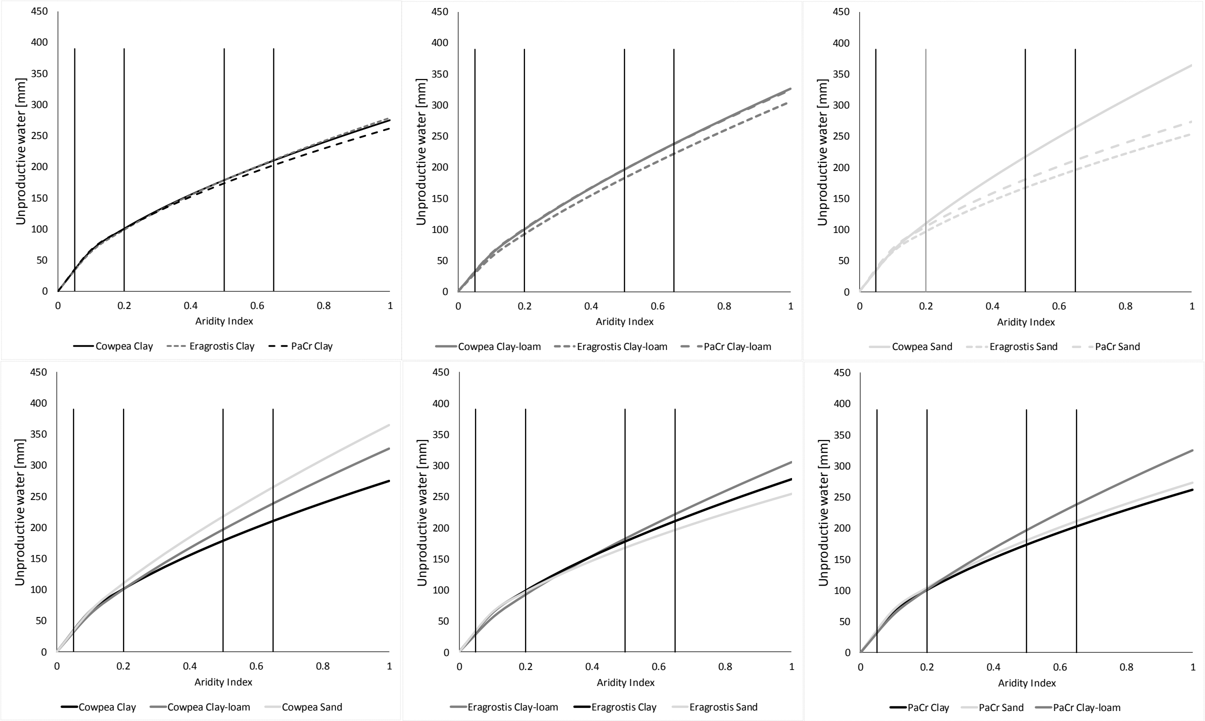


Figure 4-5 Trendlines derived from the relationship between unproductive water [mm] lost and the aridity index. Vertical lines demarcate the various aridity index categories.

4.3.2.1 Clay Soils

As with yields, transpiration increases with increasing AI categories in all three cropping systems. Clay soils also transpire slightly less than the other soil types except in the dry sub-humid category. Cowpea transpires on average 36% of the total (sum of transpiration, evaporation, drainage and interception) (CV =77%) whereas *Pasture* transpires 32% but slightly more consistently (CV =73%) across the aridity range. PaCr only transpires 26% with very high variability (CV=87%) than both monocropping systems. There is also a decreasing trend in the sub-humid transpiration from cowpea with the highest to PaCr with the lowest.

When considering the evaporation in clay soils what becomes clear is that evaporation is the dominant contributor (> 50%) of unproductive water loss, with interception contributing to this. With evaporation having an inverse relationship with transpiration, cowpea loses the least to evaporative water loss (51%), then pasture with 65% and PaCr to 74%. Evaporation drastically increases from the arid to semi-arid category.

Drainage is also a very small part of the water loss proportion in clay soils due to the higher water holding capacity and only occurs in the sub-humid category. There is also more water lost in the cowpea (6.12 %) cropping system versus the pasture (3.03 %) and *PaCr* systems (0.15 %).

When combining all the unproductive water lost in clay soils and comparing the different cropping systems, the unexpected result is that there is very little difference between the three cropping systems (see Figure 4-5).

4.3.2.2 *Clay-Loam Soils*

As with the clay soils, transpiration increases with increasing AI categories in all three cropping systems. Clay-loam soils transpire more than clay soils and very similar amounts compared to sandy soils. Transpiration increases with an increase in the AI in all three cropping systems as with clay soils with noticeably higher sub-humid transpiration amounts relative to clay. Cowpea often transpires more (39%; CV=75%) than pasture (34%; CV=73%) but less consistently across the aridity range.

When considering the clay-loam soils, evaporation is again the dominant contributor of unproductive water loss, with interception contributing to this. Cowpea loses the least to evaporative water loss (including interception) (55%), then pasture with 63% and PaCr to 62%. The higher overall evaporation is due to 17-18% more rainfall being intercepted for PaCr and pasture versus 7% for cowpea.

Drainage is again a very small proportion of the water loss proportion in clay-loam soils due to the higher water holding capacity than sand. It also mainly occurs in the sub-humid category and sometimes in the dry sub-humid category. There is also more water lost in the cowpea (6.16 %) cropping system versus the pasture (3.55 %) and *PaCr* systems (2.14 %).

When combining all the unproductive water lost in clay-loam soils and comparing the different cropping systems, the unexpected result is that there is very little difference between the three cropping systems (see Figure 4-5).

4.3.2.3 *Sandy Soils*

The same trend continues as transpiration increases with the increase in the AI in all three cropping systems. The transpiration amounts in sandy soils are higher in the semi-arid category versus clay and clay-loam soils except for PaCr. Cowpea often transpires more (38%; CV=62%) than pasture (37%; CV=55%) but again less consistently across the aridity range. PaCr transpires the same as the cowpea monocropping system but with more covariance (38%; CV=78%).

When considering the sandy soils, evaporation is again the dominant contributor of unproductive water loss, with interception contributing to this. Cowpea loses the least to evaporative water loss (45%), then pasture with 54% and PaCr to 57%. However, in terms of pure evaporation (excluding interception), sandy soils lose the least amount to evaporation (40% in sandy soils versus 63% in clay). The most striking difference is that the proportion of intercepted water is much higher in pasture and PaCr (>20%) versus 7% for cowpea. Ultimately this is lost to evaporation.

Drainage is a smaller proportion of the water loss proportion in sandy soils but due to the lower water holding capacity of sandy soils, it tends to be higher than the clay soils with a higher water holding capacity (FC = 45 % in clay versus FC = 15 % in sandy soils). There is also significantly more water lost in the cowpea (17.07 %) cropping system versus the pasture (8.3 %) and *PaCr* systems (6.43 %).

When all this data is collated and compared (see Figure 4-4 and Figure 4-5), only pasture and PaCr under sandy soil conditions save a significant amount of water relative to the cowpea monocrop. In all other cases the amount saved between cropping systems is less significant. There also seems to be an inverse relationship in that cowpea loses more water on sandy and less on clay soils whereas pasture and PaCr tend to lose less water on sandy soils and more on clay loam.

What also is striking is that there is a very strong correlation between water lost versus degree of aridity ($R^2 > 90\%$) (see Figure 4-4), being most correlated on clay-loam soils.

4.3.3 Water Use Efficiency (WUE)

There is a large range of water use efficiency (WUE) values, with few distinct differences between the different cropping systems. What is clear is that there is a greater covariance in clay soils of 93% for cowpea and decreasing toward sand which has a lower covariance of 21% for pasture. Sandy soils and to a much lesser degree clay-loam and clay soils have higher WUE levels in the drier AI categories going up to values of 21 kg mm^{-1} ha^{-1}. There is also a general trend where there are high WUE levels in in the AI<0.2, this then dips from AI>0.2 to AI<0.5. After AI>0.5, there are rather similar WUE levels. The WUE includes the baseline pasture crop of 0.4 tons per ha from the beginning of planting.

4.3.3.1 Clay

Clay is the most scattered cluster with a covariance of 93% for cowpea, followed by pasture and then PaCr. PaCr shows many crop failures with WUE values below five through the AI spectrum. Pasture and PaCr shows higher WUE in the very arid conditions, then decreases between AI>0.2 till AI<0.5, then increasing from 0.5. values beyond 0.6 on the AI and reaching WUE values of between 10-15 kg mm^{-1} ha^{-1}.

4.3.3.2 Clay Loam

Clay-loam showed slightly higher overall WUE with some of the highest PaCr WUE levels in AI > 0.5. The scatter covariance of 76% is less than clay for cowpea. Pasture has the lowest covariance of 37%.

The pattern of WUE is very similar to clay, however there is less crop failure in the AI values above 0.5, with PaCr WUE being found more regularly between five to 15 kg mm^{-1} ha^{-1}. WUE for PaCr is frequently higher in clay-loam soils, with the highest recorded WUE being 23 kg mm^{-1} ha^{-1}.

4.3.3.3 *Sand*

Sandy soils show some of the highest WUE levels in the <0.2 AI category with the pasture monocrop reaching as high as 21.39 kg mm^{-1} ha^{-1}. Sandy soils have less of a dip between AI>0.2 to AI<0.4. There seems to be more consistency here. The covariance is the lowest with pasture at 21%. WUE for PaCr is frequently higher in sandy soils right through the AI spectrum.

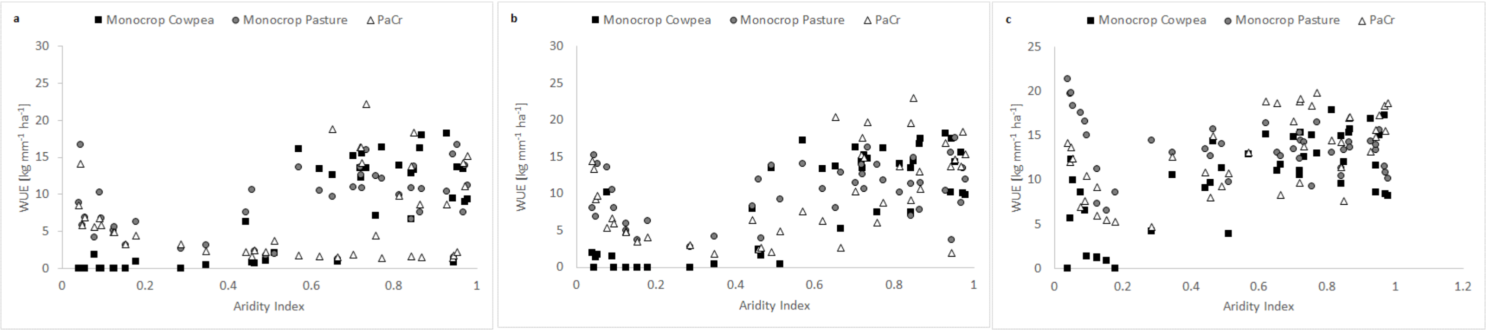


Figure 4-6 Scatter plot of water use efficiency (WUE) of clay (a) clay-loam (b) and sand (c).

4.3.4 *Competition*

4.3.4.1 *Crop Failure*

One the most obvious side effects of competition and determining factors of the success of a cropping system, is the degree of crop failure when intercropping. To demonstrate how competition played a role, cowpea as a monocrop in arid conditions can be used as a reference, showing a crop failure as a cropping system with 82%, 55% and 18% on clay, clay-loam and sand across in the arid category (see Figure 4-7). Conversely, cowpea in PaCr in arid conditions on clay, clay-loam and sand had an 82%, 100% and 91% crop failure respectively. If defining crop success in pasture as pasture providing stubble yield of 0.4 tons which remained after mowing from the last season, then there was a no crop failure. This was embraced as one of the advantages of PaCr as was thus assumed the case. Anyhow, there was no excess growth on the pasture in PaCr on clay and clay-loam, and 27% excess growth on sand indicating that stored SW played a role. With PaCr displaying a higher CV for each of the soil types, competition was assumed to be the driver for the higher CV. In summary, the CM system showed the highest rate of crop failure, however the cowpea component within PaCr showed the highest rate of crop failure. Furthermore, the more clay in the soil the higher the CV and also the greater the chance of crop failure in CM.

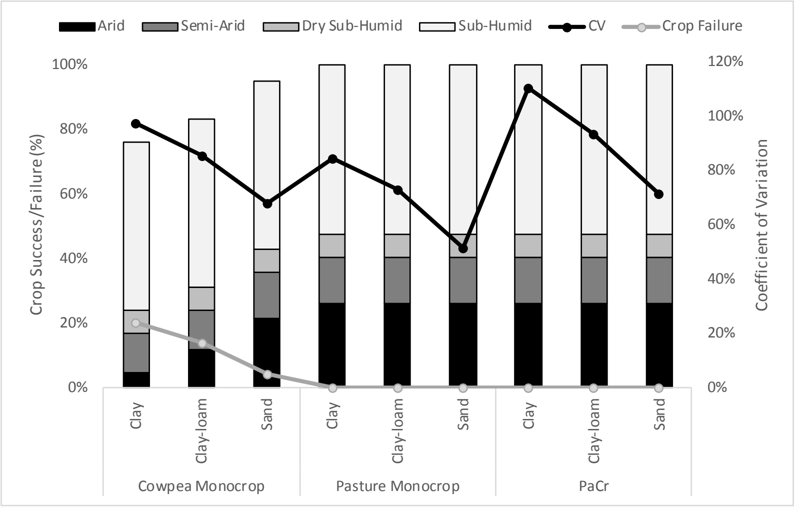


Figure 4-7 Yield stability per cropping system per aridity category based on different soil types. The dark line represents the coefficient of variation (CV). Light grey line represents crop failiure. The stacked bars represents crop system success.

Table 4-6 Crop failure rates when comparing cowpea or pasture constituents in the monocrop (Mono) control as to the cowpea or pasture in PaCr.

		Clay		Clay-Loam		Sand	
		PaCr	Mono	PaCr	Mono	PaCr	Mono
Cowpea	Arid	82%	82%	100%	55%	91%	18%
	Semi-arid	67%	17%	67%	17%	17%	0%
	Dry sub-humid	67%	0%	0%	0%	0%	0%
	Sub-humid	59%	0%	0%	0%	0%	0%
Pasture	Arid	100%	100%	100%	45%	27%	0%
	Semi-arid	50%	17%	33%	17%	0%	0%
	Dry sub-humid	0%	0%	0%	0%	0%	0%
	Sub-humid	0%	0%	0%	0%	0%	0%

4.3.4.2 LER

The Land Equivalent Ratio (LER) (see Eq. 2) is higher than one (suggesting PaCr outperformed CM and PM) for clay soils with an AI<0.5, for clay-loam with an AI>0.65 and sandy soils with an with an AI>0.65. However, in clay-loam and sand with an AI<0.5 and clay with an AI>0.65 LER was less than one suggesting CM and PM outperformed against PaCr. The LER showed no significant difference between clay types or aridity levels except that clay was significantly lower in the sub-humid category. When looking within different categories, LER on a higher clay content increased with more arid conditions (AI<0.5) whereas increased on lower clay contents with more humid conditions.

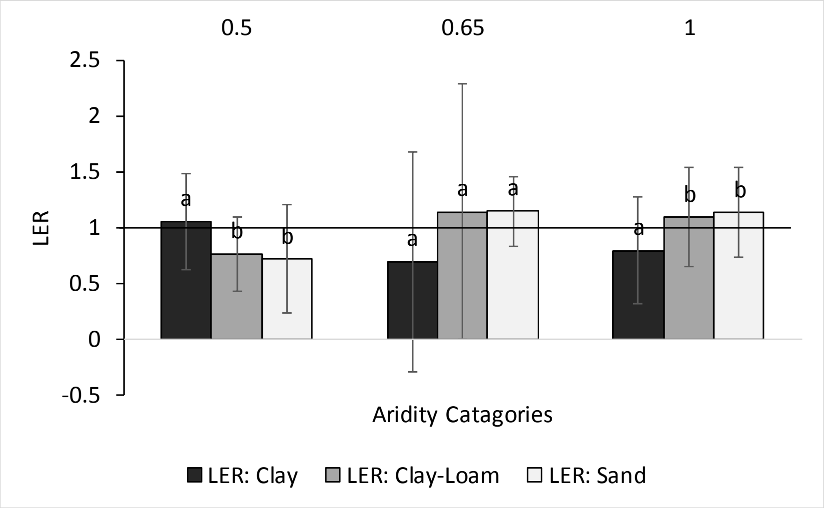


Figure 4-8 Land Equivalent Ratio (LER) for PaCr across soil type and aridity index (AI) category of AI <0.5, AI < 0.65 and AI <1.

4.3.4.3 Bivariate Analysis

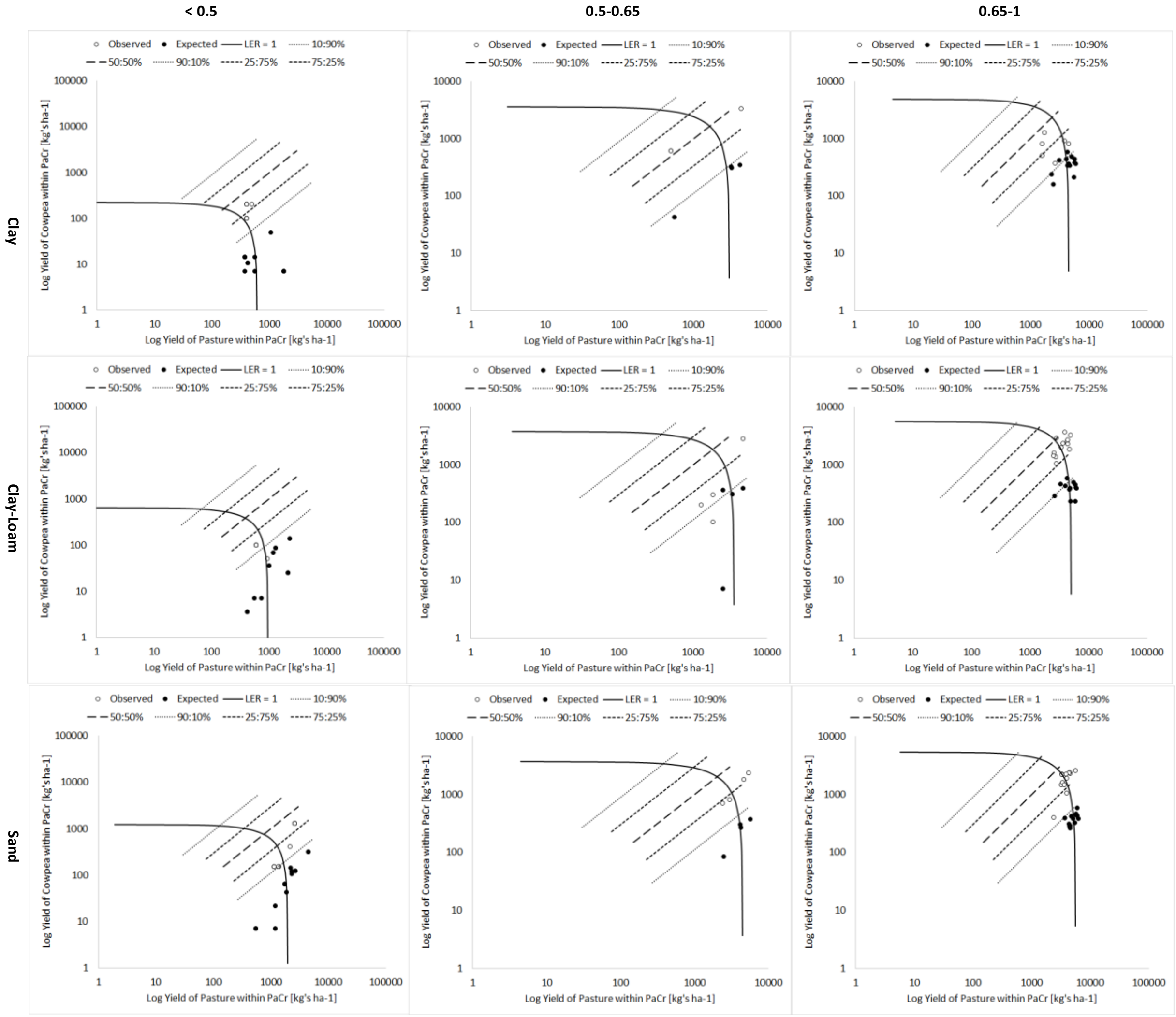


Figure 4-9 Bivariate diagram of crop competition within the Pasture Cropping system for various soil types (Clay, Clay-loam, Sand) denoted on the left of the diagram and aridity index categories denoted on the right of the diagram. Note the axes are logged. Open circles represent simulated (observed) values and closed circles represent expected yields based on Snaydon R and Satorre E 1989.

Bivariate diagrams effectively combine and express a range of competitive dynamics including resource complementarity, severity and ability in one figure as seen in

Figure 2-6. Bivariate diagrams have also not been used extensively in competition literature as discussed briefly by Bedoussac and Justes (2011), let alone for multiple plots of a long term trial which allows for all-inclusive competition dynamics to be condensed into a one graphical overview and expressing trends for the long term data of this analysis.

The bivariate diagrams in Figure 4-9 show firstly that the scatter of observed and expected have less distinct grouping in AI<0.65. In AI>0.65 the cluster of observed data are more distinguishable from the expected. Sandy soils also do tend to show more distinguishable clusters in the AI <0.65. This demonstrates that the advantages of PaCr only be more distinct in more humid conditions and that PaCr tends to have more yield advantages across a range of AI in sandy soils relative to the expected yields.

As discussed in Figure 2-6, the orientation of the observed cluster relative to the expected cluster gives more insight into the various competitive dynamics. It is clear in the data that no cluster of observed data lies convincingly beyond the LER line =1. The essentially suggests that there is no long-term simulated evidence that PaCr is more productive than the expected yields when intercropping the monocrop equivalent and the planting density stipulated. It also suggests that competitive severity is also neutral as the observed data does not all lie convincingly within the curved line. However, the data of observed values, and particularly for the humid conditions in sandy and clay-loam soils, lies in a NW orientation which shows a competitive ability being expressed by cowpea (increase based on cowpea being on the y-axis). For example, in the sandy AI>0.65 diagram, the observed cluster clearly shows a shift of the expected yield proportion line of 10:90 to 25:75 therefore cowpea increased proportionately by 15%. Pasture on the other hand shows no shift in an E or W orientation (i.e. x-axis shift) which suggests that pasture is little effected by the presence of cowpea in PaCr. These dynamics will be deconstructed for further analysis.

4.3.4.4 Competitive ability

The competitive ability (see Eq. 6) "can be measured by comparing the harvested proportions in the mixture with the expected proportions, assuming that the components have equal competitive abilities" (Snaydon R & Satorre E, 1989).

Cowpea showed a much better competitive ability than pasture. When referring to bivariate diagrams in tandem with the graphs in

Figure **4-10**, cowpea shows a positive competitive ability across all soils and aridity indices. In clay, cowpea shows a significantly lower competitive ability relative to cowpea in sand in AI<0.5 but then attains similar levels of competitive ability relative to pasture and PaCr in cay-loam and sand in AI>0.5. It seems that in AI<0.5 heavier soils suppress the competitive ability than in AI>0.5.

Pasture on the other hand showed the least negative impact on competitive ability in clay, progressively getting significantly more negative with clay-loam and sand however the scale of the differences is negligible relative to cowpea. When considering aridity, pasture shows slightly lower ability in all sub-humid conditions versus semi-arid conditions, suggesting pasture can compete better against cowpea in semi-arid conditions and less so in sub-humid conditions. This suggests that neither clay content nor aridity have a significant role in the competitive ability of pasture.

4.3.4.5 Competitive severity

The competitive severity (see Eq. 7) is the "measure of the proportionate reduction in the performance of an individual plant, caused by competition from other individuals of the same species or of another species" (Snaydon R & Satorre E, 1989).

In clay, the competitive severity for cowpea is lower in more arid (AI<0.5) conditions, then increases as it becomes more humid (AI>0.5) with little difference between clay-loam and sand. Conversely the severity decreases on clay-loam and sandy soils as the aridity index increases.

The competitive severity for pasture was significantly less than for cowpea across all soil types and aridity. However, within PM it showed no significant difference within the soil type or aridity levels. Under pasture in the semi-arid category the competitive severity increased as the water holding capacity decreased across soil types, however this reversed in the dry sub-humid and wetter category (>0.65) conditions whereby the severity decreased as the water holding capacity increased across soil types.

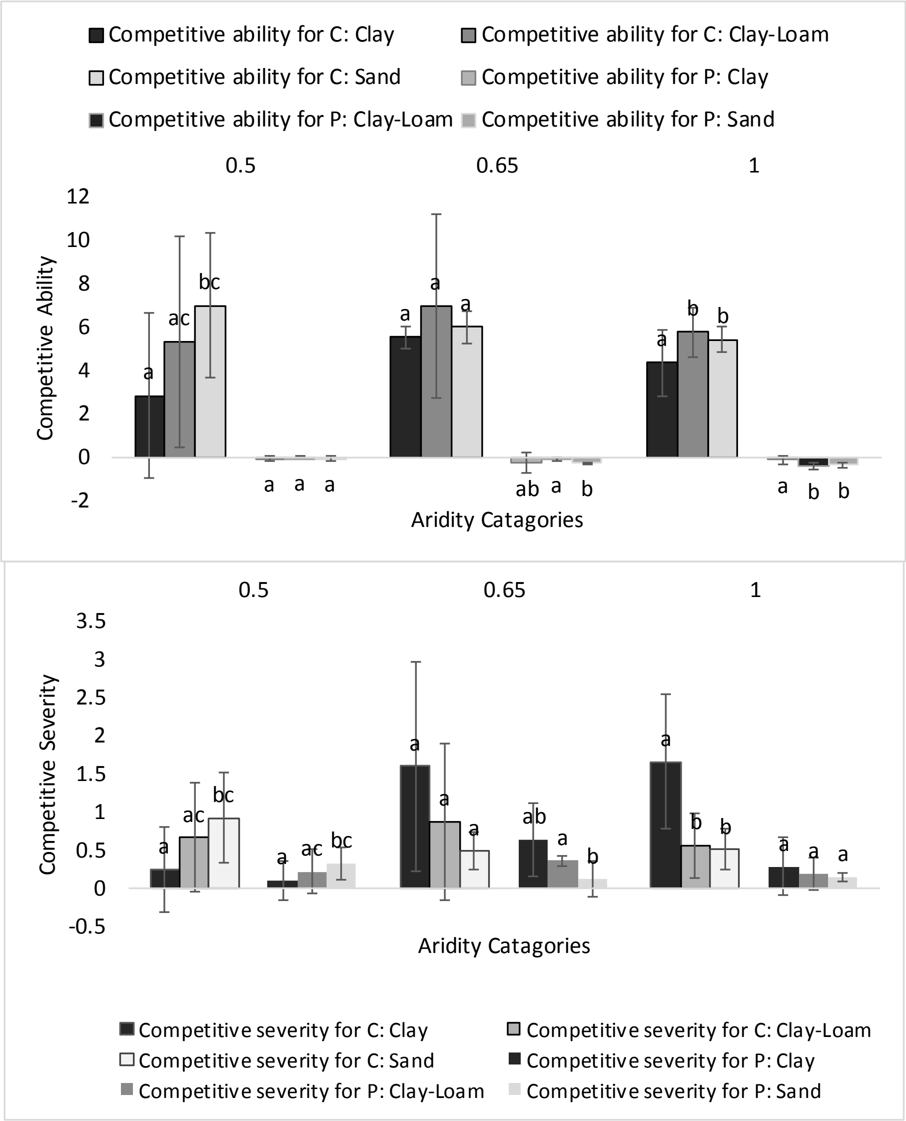


Figure 4-10 Competition indices related to the bivariate diagrams in figure 4-9. The columns are be grouped into soil type (Clay, clay-loam, sand) and aridity index category (0.5,0.65,1). Values denoted with a letter superscript above each point shows a significant difference (P<0.05).

4.3.4.6 Below Ground Competition

The primary competitive interaction with regard to SW between intercrops is the proportion of SW extracted at different depths in the soil profile via transpiration(Casper & Jackson, 1997). When assuming that evaporation only takes place in less than 0.1 m soil depth (Allen, 1998), in Figure 4-11 the clay soils show that the most water extracted for transpiration is from top 0.1 to 0.2 m. The drier the climate (e.g. Tshabong) the greater the extraction of SW from the top 0.1 m. The wetter the climate (e.g. Mtunzini) the more evenly distributed the extraction. The clay loam soils show a similar pattern however there is more water extracted from the 0.2 m layer in all three climatic regions which is part of a general more even distribution of water uptake through the soil profiles. The sandy soils show the most even distribution of water extraction through the profile, but the volume of water per layer is far less due to the lower water holding capacity. Figure 4-12 depicts the root density distribution that is used in SWB at 30,50 and 80 DAP. The curves show that the highest concentration of roots per crop are in the top 0.2 m thus reflecting where the highest proportion of water uptake and competitive interaction would be.

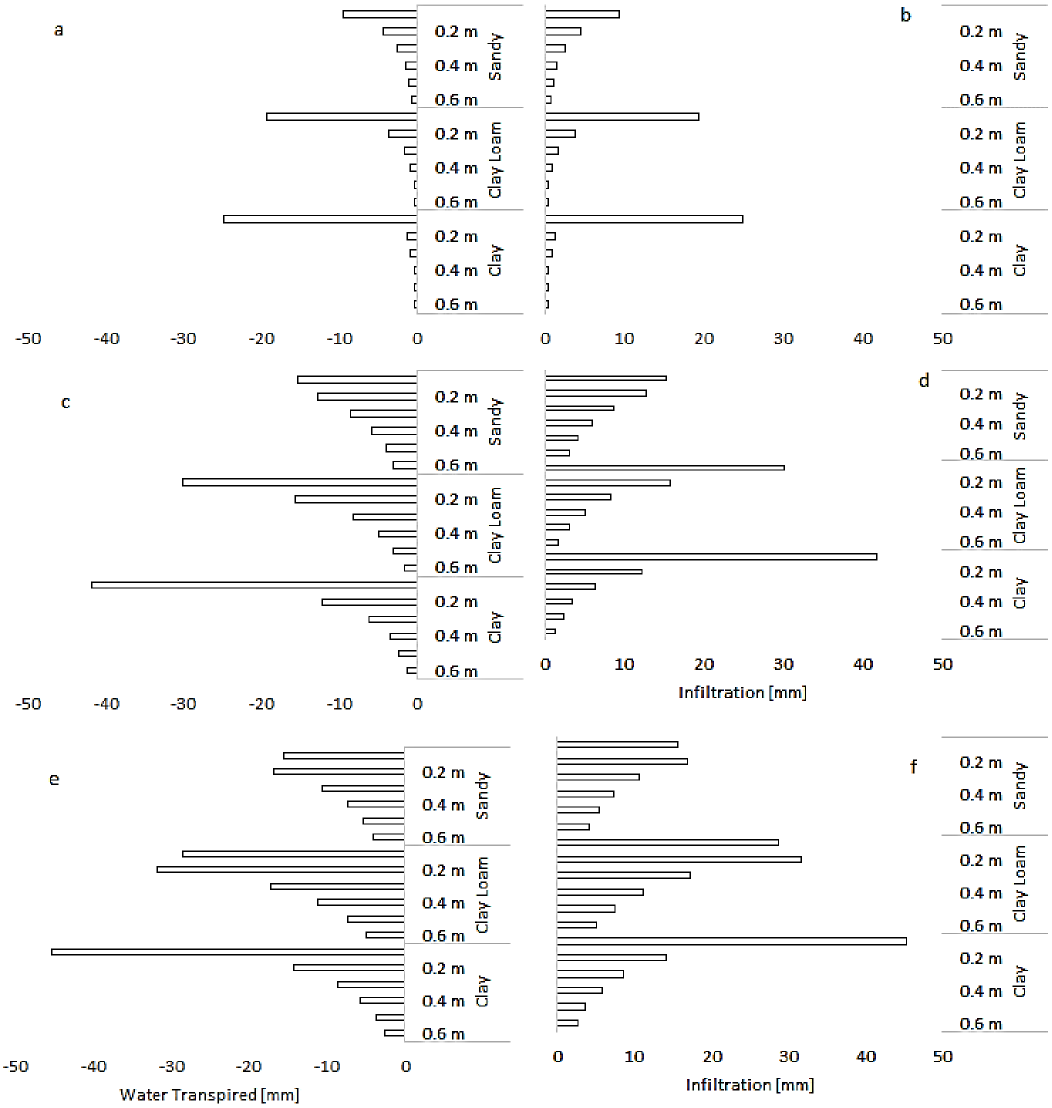


Figure 4-11 Pasture cropping (PaCr) transpiration (a,c,e) of Tshabong (a), Pretoria (c) and Mtunzini (e) and different soil levels. Infiltration (b,d,f) for Tshabong (b), Pretoria (d) and Mtunzini (f) and different soil levels.

The transpiration totals expressed in Figure 4-11 are directly calculated from empirical function for root density down the soil profile used in SWB (Annandale et al., 1999). This is graphically expressed in Figure 4-12. The highest density and concentration of cowpea roots can be found in the top 0.3 m of the soil profile at 30 DAP, then 0.4 m at 50 DAP and finally at 0.6 m at 85 DAP. The root density distribution down the soil profile is exactly the same for Pasture through till 85 DAP. There is a significant period over the growing period where the roots of the two crops draw the majority of the SW from the top 0.3 m of the soil profile. This plays a significant role in competition because rainfall in more arid areas (<0.5 on the AI) does not infiltrate deeper than 0.3 m due to the higher water holding capacity in the heavier soils such as clay and clay loam. This is clearly seen Figure 4-11 where a majority of the SW infiltrated and thus transpired is in the top 0.3 m where SW was available. In the most extreme case of clay in Tshabong (considered as arid), most water was transpired in the top 0.1 m where the highest root overlap is and where one may expect most competition for the water in that layer.

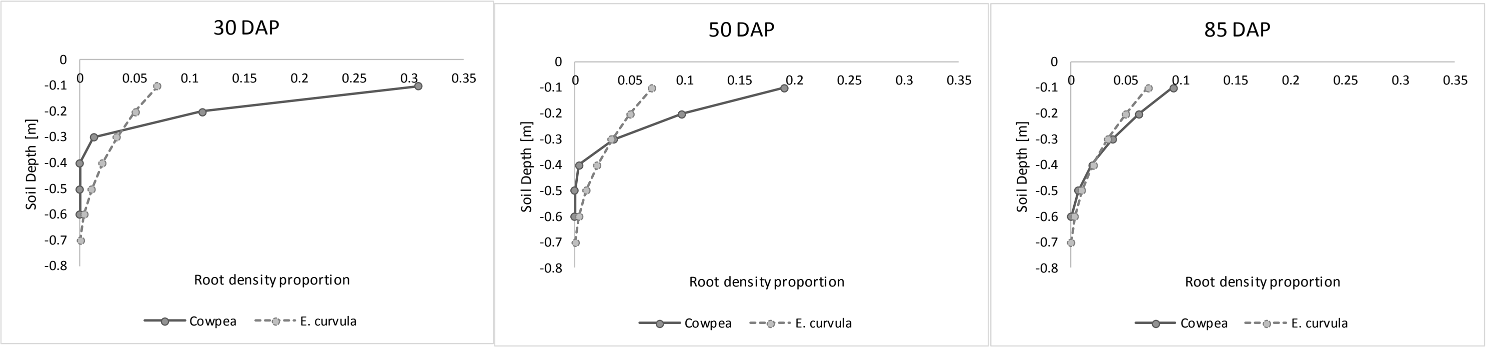


Figure 4-12 Root density as an empirical function of depth down the soil profile at 30,50 and 85 days after planting (DAP).

4.4 Discussion

4.4.1 *Yield*

The primary answer that was sought from this research was to investigate whether the merits ascribed to PaCr would be sufficient enough to make it more productive than its respective monocrop in the most destitute semi-arid regions of sub-Saharan Africa. Including answering this specific question the SWB model was used to stress test and map out the viability of PaCr across an aridity index continuum as a reference for further application in research or in industry.

With respect to PaCr being a cropping system that can yield more than the monocrop equivalent, PaCr did not outperform standard pasture monocrop in semi-arid conditions. However, PaCr did yield significantly more than cowpea in arid conditions and marginally more in semi-arid conditions (see Table 4-7). The data suggests that in terms of DM production across all aridity types, PaCr performed the best on clay soils under arid conditions and on sand in sub-humid (> 0.65) conditions. This is contrary to expectations which were that PaCr would yield better in the drier conditions than a cowpea monocrop and would show no advantage in the wetter sub-humid conditions. Ultimately PaCr would only have produced more DM if there was a shift in the water balance, where unproductive water losses in a monocropping system were retained in the rooted soil volume and were rather transpired.

4.4.2 Soil Water Balance

But as can be seen in Figure 4-5 the unproductive water losses in the simulation are remarkably similar. It is only in the sandy soils in the dry sub-humid category that we see a divergence where pasture and PaCr are losing less unproductive water than the cowpea monocrop.

Even with suspected deep drainage being virtually eliminated in PaCr relative to cowpea, particularly in the sandy soils (see Figure 4-3), evaporation unexpectedly showed no significant differences. These small differences became even more negligible because interception (which equates to intercepted water being evaporated) was much higher on pasture and PaCr versus cowpea due to the consistent DM cover and leaf litter intercepting smaller rainfall events, so when all unproductive losses are added together there is no real distinguishable difference under drier conditions (<0.5). There is a slightly lower loss of unproductive water in sandy soils by PaCr and Pasture as seen in Figure 4-5.

This difference on sandy soil hinges primarily on SW infiltrating deeper than 0.6 m into the soil profile and the root depth of cowpea being unable to access water at deeper levels. There are no roots to generate a deficit in the deeper soils so any added SW that infiltrates into these levels displaces SW into deep drainage. The converse of this is apparent with perennially deep pasture roots, also part of PaCr, where SW uptake from the beginning of the season right through to maximum roots depth causes a deficit in deeper soil layers which induces the retention of any SW displaced from shallower levels.

4.4.3 WUE

Overall, the average Water Use Efficiency (WUE) in PaCr of 9.98 versus 8.72 kg mm^{-1} ha^{-1} for the cowpea monocrop which shows that in the broadest terms PaCr is more water use efficient than cowpea. However, the pasture monocrop is more water use efficient than both at 10.89 kg mm^{-1} ha^{-1}. The WUE values are so variable that results show no significant difference. The pasture monocrop reaches as high as 21.39 kg mm^{-1} ha^{-1}. PaCr does regularly show the highest WUE but also shows some of the lowest values in the scatter of WUE data points. These values are higher than the values achieved with various grasses including *Eragrostis curvula* (Snyman, 1994). However Marais *et al* (2006) showed WUE values far more in line with the SWB simulation results. It was suggested that the lower yields in Snyman’s trials was due to no fertilisation. The higher WUE at an AI < 0.2 in pasture and PaCr suggests that higher WUE's are achieved under drier conditions. These higher WUE levels are attestable to the pasture element in PaCr or the pasture monocrop having perennially extended roots so that the majority of the water transpired is directly from SW reserves from the previous season, which is the most efficient conversion and translates directly into yield. The decline in WUE from an AI of 0.2-0.5 is most likely because water added by rainfall to the system (or denominator of the WUE function) reduces the WUE value. As the AI is semi-arid, the evaporation proportion almost diminishes the total input to the SW. As a result, water is added to the system but does not become plant available water and thus does not translate into yield. This is what reduces efficiencies (Kirkham, 2005). However, this changes beyond an AI>0.5 where there is a steady increase in WUE with increase in rainfall and then reaches an asymptote of diminishing yield returns after AI = 0.7. Using the same reasoning, the increasing rainfall proportion from an AI>0.5 is more than the maximum volume that can be intercepted and evaporated from the top 0.1 m of the soil surface thus infiltrating into the soil where the water is stored and again used in its most efficient state as a SW reserve and so increasing the WUE. This does not apply to cowpea as there are no established roots from the beginning of the season to access SW reserves and hence the higher WUE values for an AI<0.2 is not observed in the cowpea scatter plot. Cowpea only begins to have WUE of higher than 0 when the AI > 0.4. The improved WUE efficiency on sandy soil is also explained by the reasoning that smaller rainfall events that would have only infiltrated less than 0.1 m on clay soils would be able to infiltrate deeper than 0.1 m and thus would be beyond the effects of top soil evaporation and so would be conserved becoming plant available water. Therefore, the primary determinant of a high WUE is the either (1) the proportion of water that is stored in the root occupied soil volume or (2) when rainfall can pass the losses of interception and then infiltrate beyond the depth of top soil evaporation infiltrating a soil depth where roots are present. Furthermore, the SW needs to remain at a root accessible depth for the whole growing period without being forced into deeper drainage by more rainfall and thus becoming a drainage loss which reduces WUE. The next consideration is how the interspecific root interaction then shares the water in the most efficient portion of the soil described.

4.4.4 Competition

In the scenario we have established in the simulations, it is assumed that the available water discussed is the primary driving force of competition. Radiation we assume is a minimal factor due to the similar height of cowpea and pasture and the high radiation intensity experienced in all three sites. Nutrients may have played some role but with the addition of fertiliser as in the field trials, this would be minimised and was assumed as a non-limiting factor in the simulations. Water is also reiterated by Maestre *et al* (2005)*and* Ofori *et al* (1987) as being the driving force of competition in the sub-tropical and tropical regions.

Of all the cropping systems the cowpea monocrop showed the highest likelihood of crop failure which is attributed to the shallow rooted monocrop (Lightfoot, Dear, & Mead, 1987). Crop failure was most striking with cowpea in PaCr in arid conditions, with crop failure levels on clay, clay-loam and sand of 82%, 100% and 91% respectively.

With cowpea roots being shallower than pasture roots and having a limited volume of soil to forage for SW, insufficient or erratic rainfall is rapidly depleted and thus cowpea has a higher chance of crop failure, hence there being only an 18% crop success for cowpea in arid conditions on clay soils. This was aggravated in clay soils because clay has a higher water holding capacity and thus there was a much greater exposure of rain water to evaporative water loss (40% in sandy soils versus 63% in clay) as seen in Figure 4-3, while the remaining SW was transpired from the top 0.1 m as seen in the Tshabong (dry climate) region (see Figure 4-11). This meant an over dependence on a very small volume of soil. The opposite is observed in the results whereby pasture roots which have a lower dependency of the top 0.4 m had the advantage of accessing water at deeper levels once the available SW had been depleted (See Figure 4-3). This is particularly the case in sandy soils where the transpiration is spread more evenly through the soil profile thus dividing the dependency for available SW across the soil profile. This is the reason for 100% crop success on sandy soils.

These dynamics have to be considered with the competition between cowpea and pasture. The root depth for cowpea in the model was simulated to have the highest density in the top 0.4 m. As a result, cowpea and pasture roots were both occupying and foraging in the top 0.3 m and rain water rarely infiltrated the clay soil as deeply as in sandy soil (see Figure 4-11) , so the complementarity offered by different root depths could not be leveraged on clay soils as much as on sandy soils. This is again observed in Figure 4-11 whereby in arid clay soils all the water competed for is in the top 0.1 m whereas in sandy soils the uptake is spread through the profile. This also expressed by the higher incidence of crop failure and higher covariance in the clay soils versus sandy soils (see Figure 4-7).

So, when one considers the competition between cowpea and pasture in PaCr, it can thus be expected that competition is much greater for cowpea with its shallower roots and that pasture will out compete cowpea due to the deeper roots providing access to much more SW as the top 0.1 m approaches WP with increasing competition. This partially explains why the competitive effect on pasture is rather minimal relative to cowpea as seen in

Figure **4-10** where competitive ability and severity bars for pasture are much smaller than those for cowpea. This can also be seen in the bivariate diagrams in Figure 4-9 where the observed yields of pasture are not significantly less than the potential monocrop equivalent yield.

It would also be expected that competition is higher in clay soils and less so in sandy soils due to the discussed SW availability and thus competition being constrained to the top layers of the soil profile. This is not the case in arid conditions. If one compares Figure 4-13 it becomes clear that under arid conditions on clay soils cowpea is able to transpire a greater proportion of water than pasture. As the soils have less clay the pasture transpires a greater proportion relative to cowpea. The ratio is unusually acute in clay-loam. This is an example of the nuanced dynamics of competition for water in arid and semi-arid conditions. The slight increase in the yield of pasture in clay-loam soils and thus the interception of rainfall by pasture reduces the available SW for the cowpea, and thus a complete reduction in the transpiration and competitive ability of cowpea. However, on clay, pasture did not manage to yield much more than 0.4 tons and hence there was less rainfall interception and finally more water available for cowpea, which is clear in Figure 4-13. This ultimately allowed PaCr to be more productive on clay soils in arid conditions. This all indicates that minimising interception by regular mowing or grazing is an avenue that could leverage PaCr in very arid conditions.

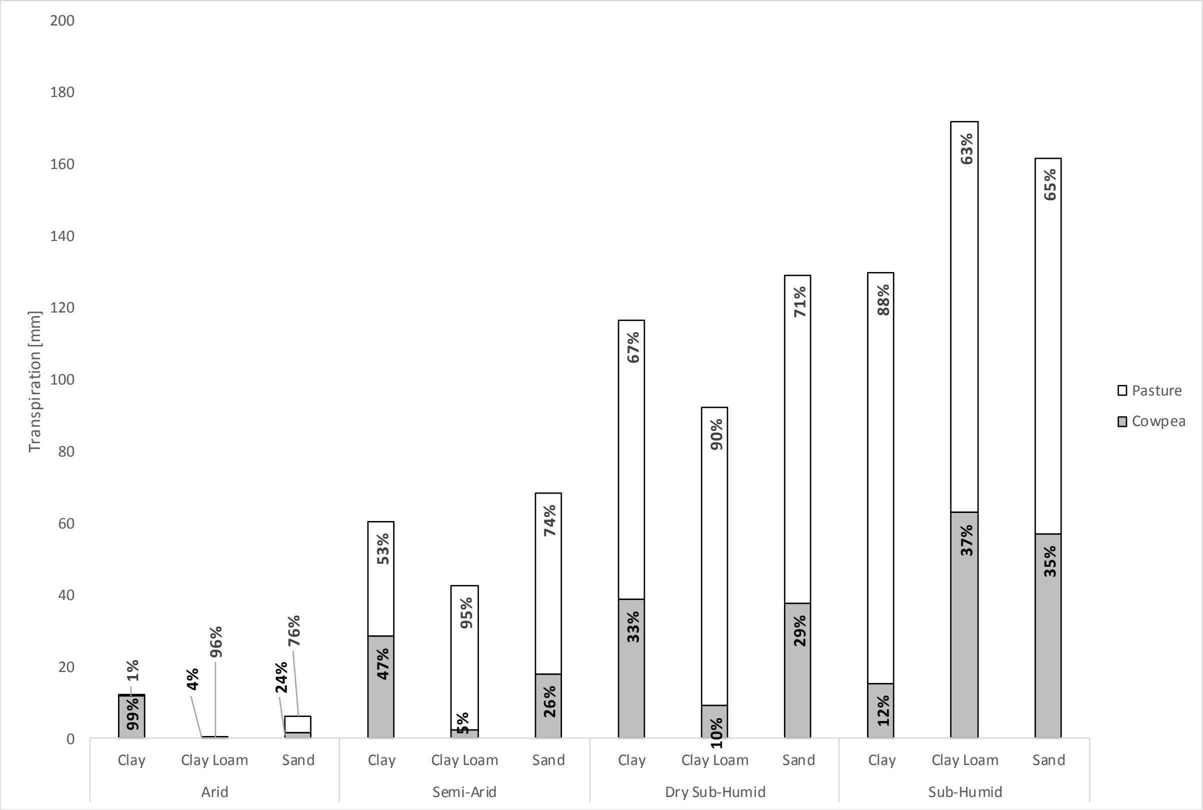


Figure 4-13 Transpiration of cowpea and E. curvula in the PaCr system on the three different soil types and aridity categories.

4.5 Conclusion

In summary, if all simulations are combined and one considers the average yield over a 14 year period for different aridity and soil categories, it allows for a framework where the three cropping systems could be planted for optimum yield (see Table 4-7) or where further simulations and detailed analysis can be carried out. PaCr was better in sub-humid conditions, irrespective of soils. When separating into soils, PaCr performed marginally better in sub-humid and humid conditions when on sandy soils. On clay-loam soils PaCr performed marginally better in sub-humid conditions. Then as discussed and rather unexpectedly, PaCr is a significantly better yielder under arid conditions on clay. This is based on impractical very low yield margins but is an interesting nuance.

Against the hypothesis that PaCr would be more successful than *E. curvula* pasture, pasture outperformed overall. With well-established roots and free from competing elements such as in PaCr, *E. curvula* is well suited to semi-arid areas. Cowpea showed better yields on heavier clay soils where the majority of the infiltration of SW never went deeper than top 0.3 m so that the shallower roots could access a majority of the precipitated water.

Table 4-7 The average yield ($\sum total\ dry\ matter\ (DM) \div years\ simulated$) within each aridity index category (arid, semi-arid, dry sub-humid and sub-humid) and for each cropping system in tons DM ha-1. Years simulated includes years with crop failure. Overall yield is for a specific cropping system irrespective of soil type. The "most suited cropping system" table below denotes which cropping system achieved the highest average yield across all seasons per soil type with the asterisk denoting (P<0.05).

Monocrop Cowpea	Arid	0.03 a	0.15 a	0.37 a	0.24 a
Monocrop Pasture	Arid	0.4 b	0.55 a	1.23 b	0.71 b
PaCr	Arid	0.43 b	0.4 a	0.54 a	0.52 a
Monocrop Cowpea	Semi-Arid	0.37 a	1.15 a	2.48 a	1.31 ab
Monocrop Pasture	Semi-Arid	1.23 a	2.18 a	3.62 a	1.95 a
PaCr	Semi-Arid	0.5 a	0.7 a	2.32 a	1.38 b
Monocrop Cowpea	Dry Sub-Humid	3.3 a	3.33 a	3.6 a	4.45 a
Monocrop Pasture	Dry Sub-Humid	2.93 a	3.9 a	4.43 a	3.6 a
PaCr	Dry Sub-Humid	0.7 a	1.9 a	4.47 a	3.07 a
Monocrop Cowpea	Sub-Humid	4.81 a	5.49 a	5.29 a	5.23 a
Monocrop Pasture	Sub-Humid	4.62 b	5.13 b	5.56 b	5.03 b
PaCr	Sub-Humid	3.28 b	5.55 ab	6.02 b	4.79 b
		Most Suited Cropping System			
Soil Type		**Clay**	**Clay-Loam**	**Sand**	**Overall**
Arid		PaCr	Pasture	Pasture*	Pasture*
Semi-Arid		Pasture	Pasture	Pasture	Pasture
Dry Sub-Humid		Cowpea	Cowpea	PaCr	Pasture
Sub-Humid		Cowpea*	Cowpea	PaCr	Cowpea

The SW results demonstrated that interestingly there is a trade-off between poor growth and thus higher evaporation from exposed soil versus better growth but greater interception which translated into evaporation. This trade-off translated into remarkably similar unproductive water loss. Where there was a slight divergence on sandy soils, it was related to benefits of deeper SW deficits of perennial pasture roots retaining the potential deep drainage that was lost in cowpea where annual shallow roots could not develop the deeper SW deficits thus incurring deep drainage losses. Ultimately the amounts of water that stayed or entered into the active root zone translated into the better WUE. The active root zone also determined the level of competition, in that if SW was only available in a root zone colonised by both crops such as in shallow clay soils, competition would be severe. Alternatively, if SW is available at different depths by deeper perennial roots, competition severity is reduced and complementarity is achieved.

The next step from observing that PaCr performs better in humid conditions is of course how radiation influences the competitive outcome. As more SW is available for growth, LAI, height and thus FI is much greater sooner, which inevitably means more shading. Additionally, water in humid conditions is not a limiting factor and thus the next limiting factor one may assume is radiation. This ultimately leads to the conclusion that PaCr is not actually a question of water competition, as the results from SWB simulations show pasture as a monocrop is dominant, but rather is a question of competition for radiation. With resource poor farmers the nutrient limitations would also have to be considered, but is not in the scope of this studies consideration.

4.6 References

Adiku, S. G. K., Carberry, P. S., Rose, C. W., McCown, R. L., & and Braddock, R. (1995). A maize (Zea mays)-cowpea (Vigna unguiculata) intercrop model. *Ecophysiology of Tropical Intercropping*, pp. 397–406.

Allen, R. G. (1998). FAO Irrigation and Drainage Paper Crop by. *Irrigation and Drainage*, *300*(56), 300.

Annandale, J. G., Benadé, N., Jovanovic, N. Z., & Du Sautoy, N. (1999). Facilitating irrigation scheduling by means of the soil water balance model. In *WRC Report No. 753/1/99*.

Annandale, J. G., Jovanovic, N. Z., Campbell, G. S., Du Sautoy, N., & Benadé, N. (2003). A two-dimensional water balance model for micro-irrigated hedgerow tree crops. *Irrigation Science*, *22*(3–4), 157–170.

Anyia, A. O., & Herzog, H. (2004). Water-use efficiency, leaf area and leaf gas exchange of cowpeas under mid-season drought. *European Journal of Agronomy*, *20*(4), 327–339.

Balasubramanian, A. (2014). *Agro-Ecological Zones*. (March).

Barrett-Lennard, P., Dolling, P., & Ferris, D. (2010). *The advantages and disadvantages of pasture cropping in Farmer ' s perceptions*.

Baumann, D. T., Bastiaans, L., Goudriaan, J., Van Laar, H. H., & Kropff, M. J. (2002). Analysing crop yield and plant quality in an intercropping system using an eco-physiological model for interplant competition. *Agricultural Systems*, *73*(2), 173–203.

Bedoussac, L., & Justes, E. (2011). A comparison of commonly used indices for evaluating species interactions and intercrop efficiency: Application to durum wheat-winter pea intercrops. *Field Crops Research*, *124*(1), 25–36.

Beletse, Y. G. (2006). *Modelling the soil water and salt balance of planted pastures irrigated with sodium sulphate rich mine effluent*. University of Pretoria.

Bertness, M. D., & Callaway, R. (1994). Positive interactions in communities. *Trends in Ecology and Evolution*, *9*(5), 187–191.

Brisson, N., Bussiere, F., Ozier-Lafontaine, H., Tournebize, R., & Sinoquet, H. (2004). Adaptation of the crop model STICS to intercropping. Theoretical basis and parameterisation N. *Agronomie*, *24*(24), 409–421.

Bruce, S. E., Howden, S. M., Graham, S., Seis, C., Ash, J., & Nicholls, A. O. (2005). *Pasture-cropping: Effect on biomass, total cover, soil water and nitrogen*. (Chittelborough 1992), 141–147.

Caldwell, R. M., & Hansen., J. W. (1993). Simulation of multiple cropping systems with CropSys. In *Systems approaches for agricultural development 2* (p. 397–412.). Springer Science & Business Media.

Campbell G. S., & Diaz, R. (1988). *Simplified Soil-Water Balance Models to Predict Crop Transpiration* (F. R. Bidinger & C. Johansen, Eds.). Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics.

Carberry, P. S., McCown, R. L., Muchow, R. C., Dimes, J. P., Probert, M. E., Poulton, P. L., & Dalgliesh, N. P. (1996). Simulation of a legume ley farming system in northern Australia using the Agricultural Production Systems Simulator. *Australian Journal of Experimental Agriculture, 36*(8), 1037–1048.

Casper, B. B., & Jackson, R. B. (1997). Plant competition underground. *Annu. Rev. Ecol. Syst.*, *28*, 545–570.

Chaves, M. M., Pereira, J. S., Maroco, J., Rodrigues, M. L., Ricardo, C. P. P., Osório, M. L., … Pinheiro, C. (2002). How plants cope with water stress in the field. Photosynthesis and growth. *Annals of Botany*, *89*(SPEC. ISS.), 907–916.

Chikowo, R., Corbeels, M., Tittonell, P., Vanlauwe, B., Whitbread, A., & Giller, K. E. (2008). Aggregating field-scale knowledge into farm-scale models of African smallholder systems: Summary functions to simulate crop production using APSIM. *Agricultural Systems*, *97*(3), 151–166.

Christine Jones. (1999). Cropping native pasture and conserving biodiversity: a potential technique. In *Conservation and Production in Grassy Landscapes.* Clare, South Australia.

Colom, M. R., & Vazzana, C. (2001). Drought stress effects on three cultivars of Eragrostis curvula: Photosynthesis and water relations. *Plant Growth Regulation*, *34*(2), 195–202.

Conway, G., & Toenniessen, G. (1999). Feeding the world in the twenty-first century. *Nature*, *402*(6761 Suppl), C55–C58.

Corbett, E. S., Crouse, & Robert P. (1968). Rainfall interception by annual grass and chaparral . . . losses compared. *U.S. Forest Serv. Res. Paper PSW*.

Coucheney, E., Buis, S., Launay, M., Constantin, J., Mary, B., & Cort, D. (2015). Environmental Modelling & Software Accuracy , robustness and behavior of the STICS soil e crop model for plant , water and nitrogen outputs : Evaluation over a wide range of agro-environmental conditions in France. *Environmental Modelling & Software*, *64*(64), 177–190.

Craig, P. R., Badgery, W., Millar, G., & Moore, A. (2015). Achieving modelling of pasture-cropping systems with APSIM and GRAZPLAN. *Proceedings of the 17th ASA Conference - Building Productive, Diverse and Sustainable Landscapes*, (September), 2013–2016.

Descheemaeker, K., Amede, T., & Haileslassie, A. (2009). *Livestock and water interactions in mixed crop-livestock farming systems of sub-Saharan Africa: interventions for improved productivity*.

Finlayson, J. D., Lawes, R. A., Metcalf, T., Robertson, M. J., Ferris, D., & Ewing, M. A. (2012). A bio-economic evaluation of the profitability of adopting subtropical grasses and pasture-cropping on crop-livestock farms. *Agricultural Systems*, *106*(1), 102–112.

Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., & Holling, C. S. (2004). Regime Shifts, Resilience, and Biodiversity in Ecosystem Management. *Annual Review of Ecology, Evolution, and Systematics*, *35*(2004), 557–581.

Fukai, S., & Trenbath, B. R. (1993). Processes determining intercrop productivity and yields of component crops. *Field Crops Research*, *34*(3–4), 247–271.

Glatzel, K., Conway, G., Alpert, E., & Brittain, S. (2014). *No ordinary matter: Conserving, restoring and enhancing Africa's soils*. (December), 40.

Glover, J., Duggan, J., & Jackson, L. (2010). *A novel perennial pasture and winter wheat conservation agriculture intercrop system for central USA*. 1–4.

Goldberg, D. E. (1996). Competitive ability: Definitions, contingency and correlated traits. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *351*(1345), 1377–1385.

Hacker, R. B., Robertson, M. J., Price, R. J., & Bowman, A. M. (2009). Evolution of mixed farming systems for the delivery of triple bottom line outcomes: A synthesis of the Grain & Graze program. *Animal Production Science*, *49*(10), 966–974.

Hatfield, J. L., Sauer, T. J., & Prueger, J. H. (2001). Managing Soils to Achieve Greater Water Use Efficiency : A Review Managing Soils to Achieve Greater Water Use Efficiency : A Review. *Agronomy Journal*, *93*, 271–280.

Heuzé, V., Tran, G., Giger-Reverdin, S., Renaudeau, D., Bastianelli, D., & Lebas, F. (2015). Cowpea (Vignia unguiculata) forage. Feedipedia, a programme by INRA, CIRAD, AFZ and FAO. Retrieved from Feedipedia website:

Holmgren, M., Scheffer, M., & Huston, M. A. (2009). The Interplay of Facilitation and Competition in Plant Communities. *Ecology*, *78*(7), 1966–1975.

Huth, N. I., Bristow, K. L., & Verburg, K. (2012). Swim3: Model use, calibration, and validation. *American Society of Agricultural and Biological Engineers*, *55*(4), 1303–1313.

Johnston, W. H., Koen, T. B., & Shoemark, V. F. (2002). Water use, competition, and a temperate-zone C4 grass (Eragrostis curvula (Schrad.) Nees. complex) cv. Consol. *Australian Journal of Agricultural Research*, *53*(6), 715–728.

Jones, H. G. (1998). Stomatal control of photosynthesis and transpiration. *J Exp Bot*, *49*(July 1997), 387–398.

Kabirizi, J., Ziiwa, E., Mugerwa, S., Ndikumana, J., & Nanyennya, W. (2013). *Dry season forages for improving dairy production in smallholder systems in Uganda*. *1*, 212–215.

Keating, B. A., Carberry, P. S., Hammer, G. L., & Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N., Meinke, H., Hochman, Z. and McLean, G. (2003). *An overview of APSIM, a model designed for farming systems simulation* (pp. 267–288). pp. 267–288.

Kiniry, J. R., Williams, J. ., Gassman, P. ., & Debaeke, P. (1992). A General, Process-Oriented Model for Two Competing Plant Species. *Transactions of the ASAE*, *35*(3), 801.

Kirkham, M. B. (2005). Water-Use Efficiency. *Encyclopedia of Soils in the Environment*, 315–322.

Knörzer, H., Graeff-Hönninger, S., Müller, B. U., Piepho, H.-P., & Claupein, W. (2010). A Modeling Approach to Simulate Effects of Intercropping and Interspecific Competition in Arable Crops. *International Journal of Information Systems and Social Change*, *1*(4), 44–65.

Lawes, R. A., Ward, P. R., & Ferris, D. (2014). Pasture cropping with C4 grasses in a barley-lupin rotation can increase production. *Crop and Pasture Science*, *65*(10), 1002–1015.

Lightfoot, C. W. F., Dear, K. B. G., & Mead, R. (1987). *lIntercropping sorghum with cowpea in dryland farming systems in Borswana. II. Comparative stability of alternative cropping systems*. *23*, 435–442.

Lightfoot, C. W. F., & Tayler, R. S. (1987). Intercropping sorghum with cowpea in dryland farming systems in Botswana. I. Field experiments and relative advantages of intercropping. *Experimental Agriculture*, *23*(04), 425–434.

Liu Guobin, L., Kemp, D. R., & Liu, G. B. (1992). Water stress affects the productivity, growth components, competitiveness and water relations of phalaris and white clover growing in a mixed pasture. *Australian Journal of Agricultural Research*, *43*(3), 659–672.

Lodge, G. M., & Mccormick, L. H. (2006). Pasture cropping in northern NSW – do the numbers for plant available water stack up? *Proceedings of the 25th Annual Conference of The Grassland Society of NSW*, (1), 166–168.

Lowenberg-DeBoer, J., Krause, M., Deuson, R., & Reddy, K. C. (1991). Simulation of yield distributions in millet-cowpea intercropping. *Agricultural Systems*, *36*(4), 471–487.

Maestre, F. T., Valladares, F., & Reynolds, J. F. (2005). Is the change of plant-plant interactions with abiotic stress predictable? A meta-analysis of field results in arid environments. *Journal of Ecology*, *93*(4), 748–757.

Marais, D., Rethman, N., & Annandale, J. (2006). Dry matter yield and water use efficiency of five perennial subtropical grasses at four levels of water availability. *African Journal of Range and Forage Science*, *23*(3), 165–169.

Millar, G. D., & Badgery, W. B. (2009). Pasture cropping: A new approach to integrate crop and livestock farming systems. *Animal Production Science*, *49*(10), 777–787.

Morris, R. A., & Garrity, D. P. (1993a). Resource capture and utilization in intercropping; non-nitrogen nutrients. *Field Crops Research*, *34*(3–4), 319–334.

Morris, R. A., & Garrity, D. P. (1993b). Resource capture and utilization in intercropping: water. *Field Crops Research*, *34*(3), 303–317.

Mureithi, S. M., Verdoodt, A., Njoka, J. T., Gachene, C. K. K., & Ranst, E. Van. (2015). *Benefits Derived From Rehabilitating a Degraded Semi-Arid Rangeland in Communal Enclosures , Kenya*.

Murungweni, C., Van Wijk, M. T., Smaling, E. M. A., & Giller, K. E. (2016). Climate-smart crop production in semi-arid areas through increased knowledge of varieties, environment and management factors. *Nutrient Cycling in Agroecosystems*, *105*(3), 183–197.

Natarajan, M., & Willey, R. W. (1986). *Field Crops Research The effects of water stress on yield advantages of intercropping systems*. *13*, 117–131.

Njoka-Njiru, E. N., Njarui, M. G., Abdulrazak, S. A., & Mureithi, J. G. (2006). Effect of intercropping herbaceous legumes with napier grass on dry matter yield and nutritive value of the feedstuffs in semi-arid region of Eastern Kenya. *Agricultura Tropica et Subtropica*, *39*(4), 255–267.

Nkonya, E., Gerber, N., von Braun, J., De Pinto, A., & Braun, J. Von. (2011). Economics Of Land Degradation. *IFRI Issue Briefs*, *68*(September), 1–7.

O'Callaghan, J. R., Maende, C., & Wyseure, G. C. L. (1994). Modelling the intercropping of maize and beans in Kenya. *Computers and Electronics in Agriculture*, *11*(4), 351–365.

Ofori, F., & Stern, W. R. (1987). Cereal–Legume Intercropping Systems. *Advances in Agronomy*, *41*(C), 41–90.

Orin Ray Clark. (1940). Interception of Rainfall by Prairie Grasses, Weeds, and Certain Crop Plants. *Ecological Society of America*, *10*(2), 243–277.

Ozier-Lafontaine, H. F., Lafolie, F., Bruckler, L., Tournebize, A., & Mollier, A. (1998). Modelling competition for water in intercrops: theory and comparison with field experiments. *Plant and Soil*, *204*, 183–201.

Ozier-Lafontaine, H. F., Lafolie, F., Bruckler, L., Tournebize, A., & Mollier, A. (1999). Modeling soil-root water transport and competition for single and mixed crops. *Plant and Soil*, *210*, 127–143.

Rees, D. J. (1986a). Crop growth , development and yield in semi- arid conditions in botswana . ii . The effects of intercropping sorghum bicolor with vigna unguiculata. *Experimental Agriculture*, *22*, 169–177.

Rees, D. J. (1986b). The effects of population density and intercropping with cowpea on the water use and growth of sorghum in semi-arid conditions in Botswana. *Agricultural and Forest Meteorology*, *37*(4), 293–308.

Rockström, J. (2000). Water Resources Management in Smallholder Farms in Eastern and Southern Africa : an Overview. *Phys. Chem. Earth (B)*, *25*(3), 275–283.

Rockström, J., Barron, J., & Fox, P. (2002). Rainwater management for increased productivity among small-holder farmers in drought prone environments. *Physics and Chemistry of the Earth*, *27*(11–

22), 949–959.

Rockström, J., Barron, J., & Fox, P. (2003). Water Productivity in Rain-fed Agriculture: Challenges and Opportunities for Smallholder Farmers in Drought-prone Tropical Agroecosystems. *Water Productivity in Agriculture: Limits and Opportunities for Improvement*, 145–162.

Schultze-Kraft, R., Rao, I. M., Peters, M., Clements, R. J., Bai, C., & Liu, G. (2018). Tropical forage legumes for environmental benefits: An overview. *Tropical Grasslands-Forrajes Tropicales*, *6*(1), 1.

Seis, C. (2006). Pasture cropping as a means to managing land. *Australian Organic Journal*, *Winter 200*(66), 42–43.

Sekhon, H. S., Singh, G., Sharma, P., & Bains, T. S. (2010). *Water Use Efficiency Under Stress Environments*.

Sengul, S. (2003). Performance of some forage grasses or legumes and their mixtures under dry land conditions. *European Journal of Agronomy*, *19*(3), 401–409.

Shepherd, K. D., Vanlauwe, B., Tittonell, P., Giller, K. E., & Leffelaar, P. A. (2005). Exploring diversity in soil fertility management of smallholder farms in western Kenya. *Agriculture, Ecosystems & Environment*, *110*(3–4), 166–184.

Silburn, D. M., Robinson, J. B., & Freebairn, D. M. (2007). Why restore marginal cropland to permanent pasture? Land resource and environmental issues. *Tropical Grasslands*, *41*(3), 139–153.

Sinclair, T. R., Tanner, C. B., & Bennett, J. M. (1984). Water-Use Efficiency in Crop Production. *BioScience*, *34*(1), 36–40.

Snaydon R, W., & Satorre E, H. (1989). Bivariate diagrams for plant competition data modifications and interpretation. *Journal of Applied Ecology*, *26*(3), 1043–1057.

Snyman, H. A. (1990). *The influence of range condition on the hydrological characteristics in a semi-arid rangeland*. (106), 93–94.

Snyman, H. A. (1994). Evapotranspiration, water-use efficiency and quality of six dryland planted pasture species and natural vegetation, in a semi-arid rangeland. *African Journal of Range and Forage Science*, *11*(3), 82–88.

Snyman, H. A. (1999). Quantification of the soil-water balance under different veld condition classes in a semi-arid climate. *African Journal of Range Forage Science*, *16*(2), 108.

Snyman, H. A. (2005). Rangeland degradation in a semi-arid South Africa - I: Influence on seasonal root distribution, root/shoot ratios and water-use efficiency. *Journal of Arid Environments*, *60*(3), 457–481.

Valbuena, D., Erenstein, O., Homann-Kee Tui, S., Abdoulaye, T., Claessens, L., Duncan, A. J., … van Wijk, M. T. (2012). Conservation Agriculture in mixed crop-livestock systems: Scoping crop residue trade-offs in Sub-Saharan Africa and South Asia. *Field Crops Research*, *132*, 175–184.

Van Duivenbooden, N., Pala, M., Studer, C., Bielders, C. L., & Beukes, D. J. (2000). Cropping systems and crop complementarity in dryland agriculture to increase soil water use efficiency: a review. *NJAS - Wageningen Journal of Life Sciences*, *48*(3), 213–236.

Vandermeer, J., & Schultz, B. (1990). *Agroecology* (S. R. Gliessman, Ed.).

Vohland, K., & Barry, B. (2009). A review of in situ rainwater harvesting (RWH) practices modifying landscape functions in African drylands. *Agriculture, Ecosystems and Environment*, *131*(3–4), 119–127.

Wahua, T. A. T., Babalola, O., & Aken'ova, M. E. (1981). Intercropping morphologically different types of maize with cowpeas: LER and growth attributes of associated cowpeas. *Experimental Agriculture*, *17*(4), 407–413.

Ward P. R., Lawes, R. A., & Ferris, D. (2014). Soil-water dynamics in a pasture-cropping system. *Crop and Pasture Science*, *65*(10), 1016–1021.

White, C. (2012). *Pasture Cropping*. *42*(7).

Willey, R. W. (1990). Resource use in intercropping systems. *Agricultural Water Management*, *17*(1), 215–231.

Winterbottom, R., Reij, C., Garrity, D., Glover, J., Hellums, D., McGahuey, M., & Scherr, S. (2013). Improving land and water management. *World Resources Institute*, (October), 1–44.

Yaacob, O., & Blair, G. J. (1981). Effect of legume cropping and organic matter accumulation on the infiltration rate and structural stability of a granite soil under a simulated tropical environment. *Plant and Soil*, *60*(1), 11–20.

5. General Conclusion

Under the field trials, PaCr was assessed under two very different seasons, which showed compelling results that would lead one to conclude that PaCr is more successful than cowpea and pasture. The successful adaptation and robustness of the SWB model to the very different season and conditions of 2013-14 and 2015 was an encouraging result. The simple approach of inserting a second crop and applying the one dimensional above and below ground approach worked well considering the scale of adaptation and as a first phase. With the adaptation of the SWB model and running the PaCr system over 14 years and on different soils, the more long-term and thus complete the overview of PaCr is versus CM and PM. DM yields from PaCr were not better than pure pasture in all but a few unlikely circumstances such as on arid clay and under very wet conditions. Also, the subtle trade-off of gaining SW from reduced evaporation through increased FI of radiation was lost due to increased canopy rainfall interception, thus making the water balance less favourable for PaCr as was anticipated. Surprisingly the unproductive water losses were very similar and predictable and only showed some divergence on sandy soils under humid conditions. In conclusion, PaCr is a better cropping system for forage cowpea than as a cowpea monocrop for food. Simple pasture appears to be the most effective approach to higher DM yields and WUE.