Direct and indirect methods of estimating lucerne (*Medicago sativa*) yield

by

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Thesis presented in partial fulfillment of the requirements for the degree of

Master of Agricultural Science (Agronomy)

at

Stellenbosch University

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December 2019

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Abstract

Lucerne (*Medicago sativa)* is an important drought tolerant fodder crop which plays an important role in providing feed for livestock in South Africa. Currently, the standard method for determining fodder on offer is the cut-and-dry method, which is time consuming, costly and labour intensive. There is therefore a need to find alternative non-destructive methods that can be used to accurately estimate lucerne yield in a time-efficient manner. The aim of this study was to calibrate a rising plate meter (RPM), ceptometer, meter ruler and canopy cover using an unmanned aerial vehicle (UAV) to estimate lucerne herbage yield. Data was collected from January 2015 till February 2018 with a break from June 2016 to June 2017. The study trial was conducted from July 2017 to February 2018 on existing lucerne trial plots under full irrigation at the Elsenburg Research Farm outside Stellenbosch. The first objective was to determine yield potential of lucerne cultivars available commercially in South Africa. Herbage yield data for 2015 was used to determine yield potential of different cultivars. Dormancy class did not affect herbage production in this study. The second objective was to calibrate indirect methods namely RPM, ceptometer and meter ruler, for estimating lucerne yield. Linear and quadratic regressions were calculated to estimate the accuracy of the RPM, ceptometer and meter ruler. Coefficients of determination derived from three yield estimations were significant ($p<0.05$). The RPM had the best coefficient of determination of $r^2 = 0.69$ ($p<0.05$) compared to the other instruments. Operation was fairly easy and it achieved its objective of cutting down on time. It worked best on the months where lucerne production was low. The ceptometer ($r^2 = 0.55$) was highly weather dependent as it worked best on clear sunny days and was affected on days with clouds and morning dew. The meter ruler was quick and easy to use to collect data. However, it could not produce a high coefficient of determination ($r^2 = 0.50$). The third objective was to develop ways to use digital data collected with a UAV for estimating lucerne yield. Linear and quadratic regressions were also calculated to estimate accuracy of the UAV canopy cover. The UAV canopy cover estimations produced the lowest coefficient of determination of $r^2 = 0.45$ compared to the other instruments. The drought experienced in the Western Cape Province during 2017 and part of 2018 cut the data collection period down to seven months from the expected twelve months. For the current study, it was concluded the RPM could be the best yield estimation instrument for estimating yield albeit there is room for it to be calibrated to get higher yield estimation accuracy. It is recommended the study is repeated over a longer period to properly calibrate all yield estimation instruments over all seasons of the year.

Opsomming

Lusern (*Medicago sativa)* is ’n belangrike droogte-tolerante voergewas wat ’n belangrike rol in veeproduksiestelsels in Suid-Afrika speel. Huidiglik is die standaardmetode om ruvoerbeskikbaarheid te bepaal, die sny-en-droog-metode, wat tydrowend, duur en arbeidsintensief is. Daar is ‘n behoefte om alternatiewe, nie-destruktiewe metodes te vind wat akkurraat en op ‘n tyd-effektiewe manier, lusernopbrengs kan skat. Die doel van die studie was om die skyfmeter (RPM), septometer, meterstok en blaredakbedekking gemeet met ‘n onbemande lugvoertuig (UAV) te kalibreer om lusernopbrengs te bepaal. Data was van Januarie 2015 tot Februarie 2018 versamel, met ‘n breek van Junie 2016 tot Junie 2017. Die studie was uitgevoer op bestaande lusernpersele onder besproeiing by die Elsenburg Navorsingsplaas buite Stellenbosch. Die eerste doelwit was om die opbrengs van lusernkultivars wat kommersiëel beskikbaar in Suid-Afrika is, te bepaal. Opbrengsdata van 2015 was gebruik om opbrengspotenisaal van verskillende kultivars te bepaal. Dormansieklasse het nie ’n invloed op produksie in hierdie studie gehad nie. Die tweede doelwit was om die indirekte metodes, naamlik die RPM, septometer en meterstok te gebruik om opbrengs te bepaal. Liniêre en kwadratiese regressies was bereken om die akkuraatheid van die drie metodes te bepaal. Koëffisiente van bepalings was afgelei van drie opbrengsskattings, was betekensivol ($p<0.05$). Die RPM het die hoogste koëffisient gehad van $r^2 = 0.69$ ($p<0.05$), vergeleke met die ander instrumente. Hantering van die RPM was redelik eenvoudig en tyd-effektief. Die effektiwiteit was egter die beste in maande wanneer lusernproduksie laag was. Die septometer ($r^2 = 0.55$) het afgehang van die weersomstandighede en het die beste op sonnige dae gewerk, en was die meeste beinvloed op oortrokke dae en deur oggenddou. Die meterstok was maklik en eenvoudig om te gebruik, maar kon nie ‘n hoë koëffisient ($r^2 = 0.50$) produseer nie. Die derde doelwit was om maniere om digitale data wat deur ’n UAV versamel was, te ontwikkel om lusernopbrengs te bepaal. Liniêre en kwadratiese regressies was ook gebruik om lusernopbrengs en die blaredak te korrelaar. Die UAV-skattings het die laagste koëffisient van $r^2 = 0.45$ tot gevolg gehad. Die droogte wat in die Wes-Kaap gedurende 2017 en 2018 ondervind was, het veroorsaak dat die dataversamelingstyd van 12 na sewe maande verkort was. Die gevolgtrekking was dat die RPM die beste opbrengskattingsinstrument was, alhoewel daar nog plek vir verbetering is om nog beter akkuraatheid te verseker. Dit word aanbeveel dat die studie herhaal word oor ‘n langer tyd om die inligting verder te verfyn.

Acknowledgments

I would like to express my sincere gratitude to the following people and institutions:

- Dr Pieter Swanepoel and Dr Johan Labuschagne for their patience, guidance and supervision that helped me through the course of my studies.
- Ms Annemarie van der Merwe and her technical staff from Elsenburg Research Farm that helped me collect my data.
- Mr Willem Botes and Dihan Slabbert for their help and services with the drone flights.
- Dr Marike Visser for her technical expertise in converting digital data into usable information.
- Prof Daan Nel for assistance with statistical analyses.
- Western Cape Agricultural Research Trust for the funding for me to enrol for my Master's degree.
- Western Cape Department of Agriculture for the use of their facilities at Elsenburg Research Farm.
- My mum and dad who for all the prayers and support they've given to me during all my studies.
- Friends and family who have always given me a word of support and encouragement during my studies.
- Finally, and most of all, I would like to thank my Lord God Almighty for giving me the strength, wisdom, ability and opportunity to undertake this research study.

Table of Contents

List of Figures

List of Tables

Abbreviations

µmol	Micromole
AVHRR	Advanced very high resolution radiometer
cm	Centimetre
DM	Dry matter
fiPAR	Fractional intercepted photosynthetic active radiation
ha^{-1}	Per hectare
kg	Kilograms
LAI	Leaf area index
LSD	Least significant difference
m^{-2}	Per square metre
m^2	Square metre
N	Nitrogen
nm	Nanometer
NDVI	Normalised difference vegetation index
P	Phosphorus
PAR	Photosynthetically active radiation
RPM	Rising plate metre
UAV	Unmanned aerial vehicle
VI	Vegetation index
Yr^{-1}	Per year

Chapter 1: Introduction

1.1 Background

Lucerne (*Medicago sativa*) is a versatile perennial fodder crop suited for grazing, silage, and hay that can be productive six years and longer (Dickinson et al. 2010). Around the world, it is one of the most grown forage crops. Its potential to produce high yields of forage even without nitrogen fertilization makes it a valuable fodder crop. It also plays an important role in crop rotation systems as it supplies substantial amounts of nitrogen to succeeding crops and has many positive effects. It is palatable, producing large dry matter (DM) quantities, especially under irrigation (Fair 1989). In South Africa, lucerne is one of the pasture hay plants mostly used (Wasserman et al. 1992). For the semi-arid regions, it is grown mainly as a rain-fed crop if rainfall is less than 500 mm and used for grazing. Under irrigation, it is mainly used for haymaking (Snyman 2014).

Herbage yield of lucerne is measured for a wide range of purposes such as DM amount, quality and its capacity to provide feed for livestock (Catchpoole and Wheeler 1992). This is to enable the farmer to know how to ration his feed for livestock and how to stock them up. The standard method for assessing lucerne herbage yield is the cut-and-dry method (Frame 1993). This is a direct harvesting method. Herbage yield is determined by weighing forage samples after oven drying to a constant weight. The yield per unit area is then calculated. While the cut-and-dry method provides accurate measures of herbage yield, it is, however, expensive and labour intensive as it may require many samples to obtain reliable estimates (Brummer et al. 1994). Symons and Jones (1971) stated different scenarios where the cut-and-dry method may not be desirable or practical:

- Where pastures or rangeland are assessed on a large scale, cut-and-dry of the herbage material becomes impractical and time-consuming.
- Sampling at high intensity is required to produce accurate measurements, so aspects such as time, labour and expenses may be excluded in the harvesting of herbage.
- Research comprises of growing plants which require frequent estimations of herbage at different growth stages. It then does not help to destroy the herbage material if it is cut.

Where destructive sampling is considered undesirable, non-destructive methods are used for yield measurement. Several non-destructive methods exist, namely: estimates of light interception using a ceptometer, a rising plate meter (RPM), meter ruler and an unmanned aerial vehicle (UAV).

A meter ruler is one of the simplest instruments used to measure plant height. It relies heavily on a positive relationship between forage yield and uncompressed canopy height. It, however, can be inaccurate to measure canopy height due to the subjectivity associated with plant or plant parts that are considered when determining mean height measure (Heady 1957).

The RPM is used for yield estimation through measurement of plant height and density. It is a non-destructive instrument that incorporates height and plant density into one measurement (Hakl et al. 2012). Researchers and producers favour it for its simplicity, ease of use, low cost, and fast rate of sampling. Earle and McGowan (1979) found it to be advantageous as it allows up to as many as 100 measurements to be made within five minutes. The plate meter can also measure a combination of dead and green forage thus making it more effective to measure total standing crop where there is a mixture of dead and green forage. Douglas and Crawford (1994), however, drew attention to the poor ability of RPM to measure lodged or overgrown pastures. They found that once herbage started reaching the stage where it was falling over the RPM's settling height increase proportionally with the increase in forage biomass. At certain stages, it even showed a decline in settling height although the pasture was still actively growing.

Optical devices that are used to indirectly measure the amount of light absorbed by the crops have an advantage as compared to destructive methods. The AccuPAR LP-80 ceptometer (Decagon devices 2001) measures sky gap fraction by comparing the intensity of photosynthetically active radiation (PAR) above to that below canopy to assess canopy light interception and leaf distribution (Zarate-Valdez et al. 2012). It comprises of a rod that has linear rays with 80 photosensors which measure PAR in the waveband regions of 400-700 nm that operate simultaneously to register PAR on the probe (Garrigues et al. 2008). It is well adapted for crops often grown in rows as this permits sampling of the inter-row space with a reduced number of measurements (Lopez-Lozano and Casterad 2013). It has been used widely for estimating leaf area index (LAI) (Cohen et al. 2000, Wilhelm et al. 2000, Vear et al. 2010).

One of the main disadvantages of these instruments includes reports of poor estimation in coniferous forests (Jonckheere et al. 2004, Weiss et al. 2004, Garrigues et al. 2008). Another disadvantage is the requirement to take numerous observations to obtain a dependable result (Breda 2003).

Another form of indirect yield measurement is the use of digital cameras attached to an unmanned aerial vehicle (UAV) to estimate plant canopy cover. The digital camera used is usually a Normalised Difference Vegetation Index (NDVI) camera. Through the use of remote sensing data, indices such as NDVI have been developed with its data used extensively for crop yield assessment and vegetation monitoring. (Hayes et al. 1982; Benedetti and Rossinni, 1993; Quarmby et al. 1993). It is an important source of information for the condition of crops. It has also been useful for yield assessment models for crops via numerous methods from simple integration to complicated transformations. NDVI reflects the greenness of vegetation thereby showing the levels of the healthiness of the vegetation (Prasad et al. 2006). Healthy vegetation will absorb mostly visible light falling on it and reflect mostly near-infrared light. Sparse or unhealthy vegetation will reflect mostly visible light and less near -infrared light (Holme et al. 1987).

The use of UAV also allows the farmer a chance to get an overall survey of his land and put his time to better use, and not walk around the field hoping to come across any areas that might have problems that need to be addressed. Yield and profit can be increased by early detecting and managing any problems associated with crop yield indicators.

There is a need to upgrade current methods used to measure lucerne yield. They are labour intensive and time-consuming. The National Lucerne Trust facilitates various cultivar evaluation trials across the country. A need was identified to evaluate alternative methods to determine lucerne dry matter compared to the cut-and-dry method.

1.2 Aim

The aim was to relate a destructive cut-and-dry method for determining lucerne yield to non-destructive estimates of yield, namely ceptometer, RPM, meter ruler and digital data using UAVs.

1.3 Objectives

To compare destructive vs non-destructive measurements of herbage yield of lucerne.

I. To determine the yield potential of lucerne cultivars available commercially in South Africa

II. To calibrate indirect methods to estimate the yield of lucerne

  - Ceptometer
  - Rising plate meter

- Meter ruler

III. To develop ways to use digital data collected with UAV’s to estimate lucerne yield

Chapter 2: Literature Review

2.1 Lucerne production

Lucerne (*Medicago sativa*) is a perennial herbaceous legume that grows in summer and supplies forage of high quality (Gault et al. 1995). It is cultivated primarily for its high-quality hay but is also used for grazing. Due to its hardiness and drought tolerance it is widely grown in rain-fed farming systems for high plant and animal productivity from October to April (Brown et al. 2005), but also performs well under irrigation. Lucerne can be grown under dryland conditions where annual summer rainfall is between 400 and 500 mm and in winter rainfall areas such as the southern Cape with 350 to 400 mm annual rainfall. Due to its deep root system, lucerne has an important advantage of being able to draw water from deep soil levels. This enables it to survive the long dry spells (De Kock 2012). The average yield of lucerne varies, depending on location, season, management and whether it is rain-fed or irrigated (Lattimore 2008). Under irrigation, lucerne requires large amounts of soil water for initial establishment (De Kock 2012). Under rain-fed systems, low seeding rates are usually recommended for adequate stand in the field as high seeding rates can cause competition for moisture between the lucerne plants (Lattimore 2008).

2.1.1 Lucerne growth and establishment

Growth and development of lucerne starts with seed germination followed by seedling establishment and growth until flowering and seed production (Undersander et al. 1997). From germination to establishment, lucerne is vulnerable to the environment. It is susceptible to frost, diseases and insect damage, but susceptibility might differ between cultivars (Hall 1998). While the seedling is developing, it is dependent on the endosperm and a delay in photosynthetic leaves development can affect establishment. Establishment is only reached when it can support itself through photosynthesis (Meyer 1999). Management practices thereafter will influence lifespan and yields (Undersander et al. 1997). Harvest intervals, time of harvest and type of harvest, fertilisation and nodulation will affect lifespan (van Oudtshoorn et al. 2001).

Lucerne is a perennial plant that stores carbohydrates in the crown and roots. These carbohydrates are useful for plant sustenance during the winter period. They are also essential for growth after cutting or in spring (Undersander et al. 1997). Regrowth after winter or a cut is normally from the crown buds but axillary buds can also have regrowth if the previous cut was not at a low height (Undersander et al. 1997). The timing of harvesting is essential to ensure long plant life. Cutting should be done at 10% flowering or when there is regrowth of new shoots from the crown (McDonald et al. 2003). Meyer (1999) states that harvesting lucerne too early can leave it with new buds that are underdeveloped. Early harvesting will also deplete the root reserves, leading to poor recovery. Late harvest can lead to new shoots growing above the cutting height which results in them being cut and poor growth in the next growing cycle. The crown must also be protected all the time when either grazing or cutting. Damage to the crown can lead to thinning of stands, increased disease susceptibility, and winterkill (Meyer and Helm 1994).

2.1.2 Morphology

The lucerne plant comprises three distinct parts; the roots, crown, and shoots with leaves. Figure 2.1 displays the three distinct parts shoots, crown and roots of lucerne. Barnes and Sheaffer (1995), as well as Teuber and Brick (1988), described the lucerne plant with a strong taproot system that can grow up to six metres in length when mature. Lateral roots may also be joined at the crown when lucerne is sown in deep, well-drained soils. The crown near the surface of the soil has a meristem that has a perennial activity to produce buds that develop into shoots. Shoots grow from two points, the crown and from axil shoots (Leach 1968). The crown shoots have a greater sink strength for assimilates and thus exhibit dominance over axil shoots through larger growth rates (Sing and Winch 1974; Gosse et al. 1988). Flowers vary from yellow, cream, white or variegated to purple, with spirally shaped seed pods being produced after they have been pollinated.

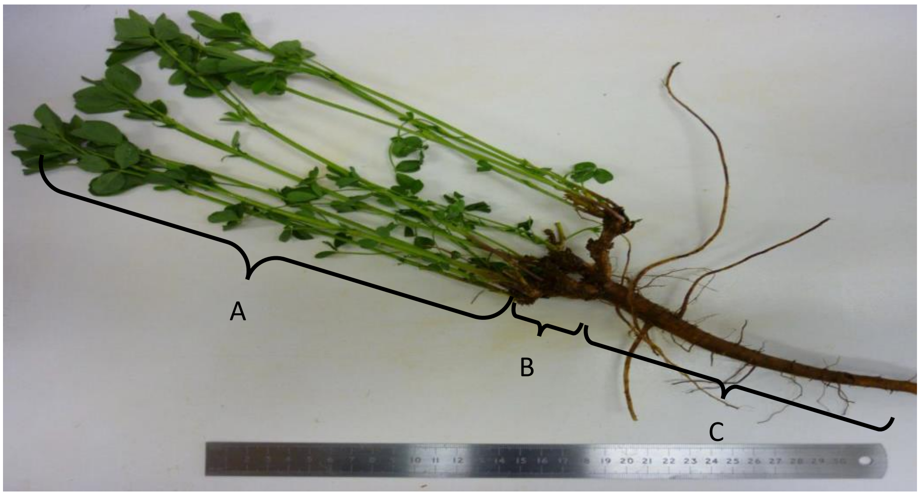


Figure 2.1: Distinct plant parts of lucerne: A) shoots B) crown and C) roots.

2.1.3 Nutrient requirements

Lucerne is a legume, thereby not requiring nitrogen (N) fertiliser as it forms a mutualistic relationship with *Rhizobium meliloti* that fixes atmospheric dinitrogen to a plant-available form of N. It has been noted by Gault et al. (1995) that lucerne improves soil structure, builds up N reserves and increases soil organic matter. It is sensitive to soil acidity and needs soils with a pH of 6.5 $_{(KCl)}$ or more for high yields (Ball et al. 2007). If the pH $_{(KCl)}$ drops below 5, growth vigour declines. Whilst resistant to brack conditions, lucerne production is also affected if pH increases above 6.5 (Dickinson et al. 2010). It has a high phosphorus demand for seedling development and rapid root growth. Potassium requirement is low during the seedling stage with demand increasing with growth. Trace elements are required in smaller amounts but are still vital to lucerne production (Dickinson et al. 2004). Due to relative immobility of trace elements, toxicity can be a problem if applied in wrong quantities (Gupta et al. 2001). Molybdenum is a trace element required for nitrogen fixation, protein synthesis and forms part of some enzymes such as nitrate reductase (Miles et al. 2000). It is also important for the uptake of other nutrients such as iron. If molybdenum is low iron uptake can be depressed (Monreal and Villavilla 1982). Sulphur (SO_4^{2-}) is required in inorganic form by lucerne though it is mainly found in organic matter form. The sulphate anion is important in legume crops such as lucerne for growth and nitrogen fixation (Miles et al. 2000). Table 2.1 shows the expected nutrient uptake in one growing season of lucerne.

2.1.4 Pests and diseases

Pests such as nematodes (*Nematoda*), leafminer (*Agromizidae*), lucerne flea (*Sminthurus viridis*), aphids (*Aphidoidea*) and white fringed beetle (*Naupactus leucoloma)* are known to have a detrimental economic effect on lucerne (Humphries and Auricht 2001). They affect lucerne productivity by hindering seedling development, slowing growth and development and plant tissue damage, which create points through which bacteria and fungi can enter (Frame et al. 1998). Agents of bacteria, fungi and viruses also influence the production of lucerne. They reduce production by lowering herbage yield (Summers and Gilchrist 1991), lowering herbage quality and prevent acclimatisation of lucerne to adverse conditions (Lennsen et al. 1991). Control of pests is normally done using chemicals, but non-chemical methods are sometimes favoured as they lower costs associated with the control. Frame et al. (1998) recommends scheduling harvests so that the life cycle of the pest is interrupted thereby reducing pest infestation on the following regrowth periods. Humphries and Auricht (2001) recommend the use of genetically resistant cultivars to control pests. Control can be done through use of cultivars resistant to the disease prevalent in the area where lucerne is being produced (Wiersma et al. 1995). Humphreys (1987) states that tillage can also be used to reduce soil-borne pathogen pressure. Crop rotation is recommended to break pest cycles, and to promote soil drainage, maintenance of plant nutrition, reduction of exposure to abiotic stresses to reduce disease incidences in the field (Frame et al. 1998).

Table 2.1: Amount of nutrients removed from the soil per t dry matter (van Oudtshoorn et al. 2001, FERTASA 2016).

Nutrient removal (kg t^{-1} dry matter)		
Nutrient	USA data	ARC data
Phosphorus	3.0	2.7
Potassium	24	21
Calcium	15	13
Magnesium	3.0	2.7
Sulphur	3.0	2.7
Boron	0.04	0.04
Manganese	0.06	0.05
Iron	0.17	0.15
Zinc	0.03	0.02
Copper	0.01	0.05
Molybdenum	0.001	0.0009

2.1.5 Dormancy

Although lucerne can produce herbage year-round, it is mainly productive during months of spring, summer, autumn (or warmer months) and becomes relatively dormant in winter. When top growth is not removed and allowed to mature, it dies back, with new growth points developing from the crown. This can happen several times ranging from three to ten per season dependent on soil moisture availability and temperature (De Kock and Birch 1980).

Winter dormancy rating (winter activity) is a key index that is used to assess the amount of winter growth in response to day length and temperature (Teuber et al. 1998). In the United States of America, the dormancy system ranges from 1 to 11, where a rating of 1 indicates highly dormant, and 11 being non-dormant in winter (Dickinson et al. 2010; Lauriault et al. 2011). In South Africa, a similar system is used, even though there is no scientifically published literature on South African dormancy classes. Generally, lucerne with a dormancy class lower than 5 is not available in South Africa. Therefore, South African lucerne being grown has dormancy classes ranging from 5 (winter dormant), 6 to 7 (intermediate dormancy), 8 (winter active) and 9 to 11 (highly winter active).

Winter dormant cultivars have a low tolerance for cold weather (Tueber et al. 1998). They grow very slowly or even cease growth and the synthesis of sugars which allows them to survive through winter (Dhont et al. 2002). Approximately 50 to 60% of total assimilated carbon is partitioned to perennial underground organs for future growth and stand persistence of lucerne (Teixeira et al. 2007). Winter dormant lucerne is also more likely suited for use in a mixture with winter crops or forages. Dickinson et al. (2010) state that when a cultivar is more winter dormant, it has a longer lifespan and is better suited for grazing. This due to the crown being just below the soil surface thus limiting damage to the points for shoot regrowth.

Winter active cultivars can produce up to 20% of their growth in winter due to the low dormancy. They tend, however, to have a short stand life. They also have a crown which protrudes high above the soil surface leaving them prone to diseases and damage of the crown by machinery. Winter active cultivars are more suited to shorter pasture phases and haymaking. They can increase forage production in environments that have predominantly winter rainfall (van Heerden 2012).

In a study conducted by van Heerden (2012) relative lucerne cover was found to be related to dormancy class. Dormancy class was found to be the most important factor in determining the yield due to its influence on lucerne cover. Cultivars which are more dormant displayed a more stable cover and more yield in the long term. It was found that the dormant cultivars were slower to establish, and they should be used in longer pasture phases. They also tended to be more productive in drier and warmer seasons as compared to winter active cultivars that fared better in cooler and moist seasons.

2.2 Biomass measurement

Biomass is one of the crop parameters used to evaluate the health status of crops, the supply of nutrients and the effects of agricultural management practices (Adamchuk et al. 2010). It is a key component of measuring yield. It is used to determine stocking rates and match forage resources to appropriate levels of utilisation, evaluate management strategies and investigate forage productivity.

According to Te' Mannetje (2000a and 2000b) biomass is measured for a wide range of purposes namely: the amount of herbage, quality of herbage, description of the botanical composition, ground cover, biological alterations in relation with the change of climate and for determining its capacity to provide livestock with feed. It is, therefore, necessary to have herbage yield estimation models that provide estimates that are as correct as possible to help with budgeting and allocation of feed on the farm. Herbage yield can be highly variable both within and between paddocks. Direct methods (cut-and-dry) therefore requires many samples to have accurate estimates. This then becomes costly in terms of labour and time. Various indirect methods exist which can be used to evaluate herbage yield, such as a disc pasture meter, ceptometer, sward stick and methods involving aerial photography.

2.2.1 Disc pasture meter

Falling plate meter

The first plate meters to be used were the falling plate meter. They were based on dropping a plate from a specified height above the canopy, measuring the settling height on a pole inserted through the centre of the plate (Douglas and Crawford 1994). Figure 2.2 displays the visual image of the falling plate meter. Inaccuracies would occur with the readings because the plates were not always dropped from the same height. This resulted in plates settling on forage at different velocities (Harmoney et al. 1997). Various materials ranging from cardboard, wood, metal or plastic have also been used unsuccessfully to construct different plate meters (Bransby et al. 1977; Gabriels and Van den Berg 1993). Several authors have suggested modifications by substituting the metal plate with other materials such as acrylic and transparent plastic with some markers or holes (Rayburn and Rayburn 1998). These holes would allow the use of the plate as a squares paper for estimating ground cover and measuring the occurrence of forage species under the sampling area. It was, however, concluded by Bransby et al. (1977) that weight and material of the disc did not affect estimation accuracy significantly if the calibration equation used was constructed using the specific plate.

Rising plate meter

The rising plate meter (RPM) is used as a grassland management tool used by various advisors and farmers. Figure 2.3 displays the visual image of the RPM. It is used to estimate forage resources to help with grazing management and feed budgeting (Lile et al. 2001). It is often used to describe the cut meadows (Honsova´ et al. 2007) and small-scale sward structure of grazed pastures (Correll et al. 2003). The RPM is a tool utilising a graduated shaft with a sliding plate to measure the amount of forage produced and its utilisation (Scrivner et al. 1986). It consists of a light horizontal plate (also known as the weighted disc) that can slide down the central and graduated shaft (Frame 1993). Forage height and density prevent the plate from falling to the ground, and a reading of the plate taken height from the shaft is related to yield using a calibration curve. Pre-established curves for calibration should be used if appropriate (Earle and McGowan, 1979), otherwise specific calibration curves should be made (Gourley and McGowan 1991).

Michell and Large (1983) described the RPM as having been successfully applied to estimate herbage mass, particularly in intensively managed pastures of uniform botanical composition. For biomass estimation of cool-season grasses such as tall fescue (*Festuca arundinacea*) and Kentucky bluegrass (*Poa pratensis*), Harmoney et al. (1997) reported correlation values of $R^2 = 0.85$ and $R^2 = 0.58$, respectively using the RPM thereby declaring it effective. Accuracy to estimate herbage yield was dependent on forage type and species. Non-jointing grass species tended to be more highly predictable compared to jointing species. Earle and McGowan (1979) found the RPM to have a positive attribute of taking large numbers of readings in a short space of time (up to 100 readings in five minutes). Compared to direct harvesting, the RPM was more efficient in reducing sampling time (4.5 hours for 800 samples for RPM as to 8.5 hours to 40 samples for direct harvest) (Gourley and McGowan 1991.)

However, the RPM has a poor ability to measure lodged and overgrown pastures. It was found once pasture reached the stage where it starts lodging, the plate meter's settling height did not increase proportionally with an increase in forage biomass. Therefore, during lodged conditions, the RPM underestimates yield. At certain points, it even showed a decline in settling height although the pasture was still actively growing (Douglas and Crawford 1994).

2.2.2 Ceptometer

The ceptometer is an instrument used to measure photosynthetic active radiation (PAR). It consists of a probe with 80 PAR quantum sensors that measure PAR, arrayed at 1.0 cm intervals beneath a light diffusing shield (Salim et al. 2015). Figure 2.4 displays the visual image of a ceptometer. McCree (1972) defined PAR as the electromagnetic radiation on the waveband between 400 – 700 nm. PAR is displayed in $\mu\text{mol m}^{-2}\text{s}^{-1}$ and the suns zenith angle in degrees (Salim et al. 2015). It has been used extensively on field trials to measure light intercepted in various field crops such as wheat (*Triticum aestivum*), maize (*Zea mays*), as well as fruit trees.

Figure 2.2: Visual image of the falling plate meter.

Figure 2.3: Visual image of the rising plate meter.

The photosynthetically active portion of the spectrum is absorbed by plant canopy for photosynthesis, which results in biomass production (Monteith 1972). Monteith (1977) also states that there is a generally linear relationship between canopy fractional intercepted PAR (fiPAR) and photosynthesis because the rate of photosynthesis is proportional to fiPAR.

Fernandez-Ordoñez and Soria-Ruiz (2017) conducted a study in Mexico to estimate the yield of maize using spot-5 satellite images and empirical methods (ceptometer). These models expressed; a) yield as a function of Normalised Difference Vegetation Index (NDVI) and b) yield as a function of leaf area index LAI. Yield sampling was conducted at physiological maturity to determine efficiency degree of the calculated prediction. The models $Y = \int(\text{NDVI})$ reported a yield value of 5.04 t ha^{-1} and $Y= \int (\text{LAI})$ reported 5.96 t ha^{-1}. This data presented 97% and 114% accuracy respectively of the true yield obtained.

Instruments closely related to the ceptometer have also been used to estimate yields of various other field crops with varying success. Murphy et al. (1995) used the capacitance meter on Kentucky bluegrass and white clover (*Trifolium repens)* pastures and obtained coefficients of variation of 29%. Meter background reading errors were deemed to have caused variability in the measurements leading to a low coefficient of determination.

Figure 2.4: Visual image of the ceptometer.

2.2.3 Meter ruler

Researchers and plant breeders consider the height of lucerne to be a key trait. It can be linked to production potential and herbage yield (Griggs and Stringer 1988; Riday and Brummer 2002; Humphries and Hughes 2006). Stem length is measured as the maximal length of the tallest stem in the areas being investigated. Stand height is defined as the vertical height from the soil surface to the tallest point on the stems (Hakl et al. 2006). Height is normally recorded at numerous developmental stages from the bud stage and throughout the season. Robins et al.

(2007) used lucerne height to assess the rate and rapidity of regrowth in spring as well as the following cuts.

The meter ruler is a simple instrument that relies on a positive relationship between herbage yield and the canopy height. It is operated by placing the base of the ruler on the soil and reading of the tip of the plant (Benseman 2013). Litherland et al. (2008) using the meter ruler developed calibration equations for pastures in New Zealand. The R^2 value varied between 0.38 and 0.56.

Closely related to the meter ruler is the sward stick which contains pasture management information on the side. It consists of a graded scale and Perspex sleeve (Benseman 2013). It has 0.5 cm graduations (Rhodes 1981). It is operated by placing it vertically in the pasture with the Perspex sleeve lowered down till it touches the highest non-flowering herbage point (Stewart et al. 2001). It has a table that relates pasture height to the estimated yield in kg DM ha^{-1} (Garrish and Roberts 1999).

2.2.4 Unmanned aerial vehicle

Remote sensing from manned aircraft and satellite platforms for agricultural management has been researched for over 60 years (Pinter et al. 2003). The unmanned aerial vehicle (UAV) demonstrates the latest method for aerial image acquisition for remote sensing data. It is a lightweight and cost-effective technology due to its miniaturised sensors for image capturing and reliability (Alkaabi and Abuelgasim 2017). UAV’s provide to the farmer a remote sensing platform with characters such as small pixel sizes and quick delivery of information for data acquisition. It enables data collection at field scale with temporal and spatial resolutions that were not previously obtainable through traditional remote sensing platforms such as satellites. The most common UAV is the quadcopter. It has cameras and sensors that detect light waves invisible to the human eye. These sensors and cameras can capture images and input such as temperature (Hafsal 2016). Figure 2.5 displays the type of UAV that can be used.

Technology involving image analysis have appeared in agronomic literature. Some of the work using these image analyses involves the development of specific computer programs that identify a required bandwidth or wavelength and converts it to a quantifiable parameter that can be analysed by statistical methods (Ewing and Horton 1999). Digital image analysis has been successfully used to estimate canopy cover. It has been successfully used to estimate canopy cover and light interception in soybean (*Glycine max*) (Purcell 2000). It has also proven to be useful after successful testing on bermudagrass (*Cynodon dactylon*) and zoysiagrass

(*Zoysia japonica*) (Richardson et al. 2001). In forestry, digital imagery has been used by taking the presence or absence of a tree canopy at specific point positions tallied for each sample point. The proportion of the sample point that falls on the canopy is considered to represent statistically the amount of forest canopy cover (Walton et al. 2008). Digital sensors have been successfully integrated onto unmanned aerial vehicles UAV's to assess crop vigour, vegetation coverage and greenness (White et al. 2012; Andrade-Sanchez et al. 2014). The estimation of vegetation indices, vegetation canopy mapping, soil and crop temperature, crop nitrogen estimation amongst many others have shown to be feasible and precise (Haboudane et al. 2004; Bernie et al. 2009). Spectral bands and vegetation indices such as Normalised Difference Vegetation Index (NDVI) have been developed from these bands (Yang et al. 2004). Normalised Difference Vegetation Index (NDVI) is an indicator based on two bands of the magnetic spectrum the near-infrared and visible light (Mkhabhela et al. 2005). It measures the greenness and vigour of vegetation (Tarpley et al. 1984). Chlorophyll pigment in vegetation causes low spectral reflectance into the visible waveband and high spectral reflectance into the near-infrared waveband (Kogan 1994). It has been used extensively to monitor crop performance, yield, and rangeland carrying capacity. Data is obtained by focusing the two wavebands that are sensitive to the vegetation information. When there is a bigger difference between the near-infrared and the visible it is an indication of more vegetation (Roderick et al. 1996). Holme et al. (1987) state that healthy vegetation reflects most of the near-infrared and will absorb large portions of visible light that falls on it. Unhealthy or sparse vegetation will be characterized by reflecting most of the visible light and less near-infrared. Both visible and near-infrared portions of the electromagnetic spectrum are moderately reflected on bare soils.

Biomass estimates acquired from NDVI may be used as a good indicator of productivity. It has been used to assess the condition of vegetation. The data obtained from advanced very high-resolution radiometer (AVHRR) has been used to assess the growth of pastures and monitor pasture productivity changes over a long-term like a 20-year period (Magsar 2004). Mitchell et al. (1990) obtained lucerne correlations of (R^2 = 0.89) using NDVI. NDVI has also been widely researched as a tool for measuring the biomass of agronomic field crops. Moges et al. (2004) found correlations of winter wheat ranging from R^2 = 0.60 to 0.78. Maize yield correlations (R^2 = 0.50 to 0.80) were reported by Ma et al. (1996) during the anthesis stage. Ma et al. (2001) also reported correlations in soybean (R^2 = 0.44 to 0.80) between the growth stages R2 through to R5 (R2 being beginning of flowering, R3 being pod development, R4 being full pod, and R5 being seed development). The highest correlations were found at the R5 stage. It was concluded that in the early reproductive stages NDVI may be used to estimate the grain yield.

Despite being a valuable vegetation index (VI) it has been noted that NDVI can be inadequate in assessing crop vegetation (Liu and Huete 1995). Vegetation indices have a saturation problem when estimating above ground yield in crops (Chen et al. 2009). This problem is characterized by the low sensitivity of VI's calculated from the red and near-infrared reflectance in response to biomass accumulated when LAI and biomass exceed a certain threshold (Gao et al. 2000; Thenkabail et al. 2000; Mutanga and Skidmore 2004). Variations in soil brightness can also produce large variations in NDVI from one image to the other (Liu and Huete 1995).

Figure 2.5: Visual image of an unmanned aerial vehicle.

2.3 Statistical methods

A correlation analysis is a statistical technique that is used to show the strength of a relationship between two or more variables (Bowerman and O'Connell 1990). The result of correlation analysis is a statistic ranging between -1 and 1 which describes it as a negative or positive correlation (Kent 2012). It describes and measures the form of relationship between two variables and allows the prediction of one variable in terms of the variation in the other. It determines the curve or line that best represents a general data set. It is useful to explain the relationship between the yield estimation instruments and the actual herbage yield (Kent 2012). Figure 2.6 displays the three different correlations A) Negative correlation, B) Positive correlation, and C) No correlation.

There are different regression models that can be used to explain a data set of linear or quadratic, cubic regressions etc. Linear regression explores the relationship that can be readily described by a straight line. It is the simplest and most commonly used regression as it solves a large number of problems (Bowerman and O'Connell 1990). In biology, however, correlations are not always in a straight line but sometimes curved, thus the need for quadratic and cubic regressions to further explain the correlation.

The R^2 is defined as the proportion of variance explained by the regression model. It indicates the proportion of variance in an independent variable that is predicted by the regression and the prediction variable. It is calculated by squaring the correlation (r) between predicted and actual value (Nagelkerke 1991). It is relied upon to explain how the variability of one factor can be affected by its relationship to the other factor. It is represented as a value between 0 and 1. A value of 0 indicates the there is no fit at all to the model whilst 1 shows there is a perfect fit (Kent 2012).

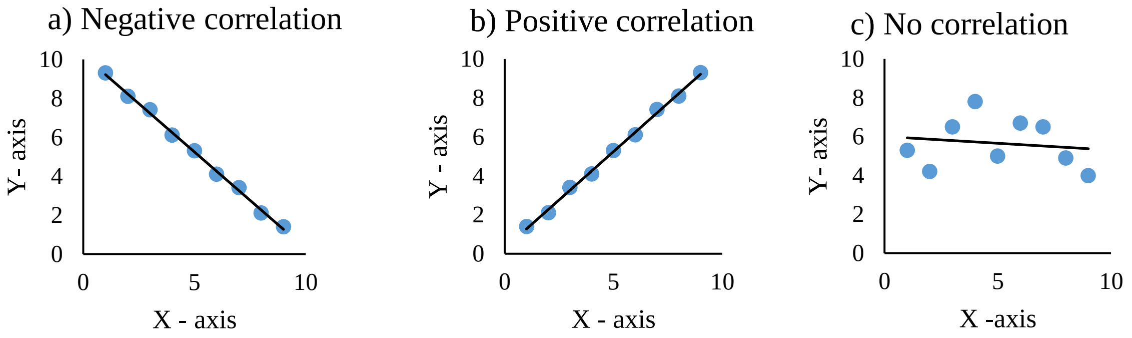


Figure 2.6: Three visual images of correlations; a) Negative correlation, b) Positive correlation, c) No correlation.

Chapter 3: Materials and methods

3.1 Site description and trial management

The experimental trial was carried out at the Elsenburg Research Farm (altitude 177m, 18°50'E, 33°51’S) of the Western Cape Department of Agriculture. It is located outside Stellenbosch in Western Cape Province, South Africa. The soils have a sandy loam texture and derived from granite (Anon 1996). They can be classified as an Oakleaf consisting of an Orthic A horizon over a Neocutanic B horizon (Soil Classification Working Group, 1991). It is a well-drained, hilly terrain. The climate is Mediterranean-type, with summers that are dry and warm to hot, with some February and March days rising to over 40 °C. The winters are cool, rainy and windy, with daytime temperatures averaging 16 °C. The mean annual rainfall in the area is 673 mm per annum (ARC-ISCW 2004). The weather data for the long term and during the duration of the study is displayed in Figure 3.1.

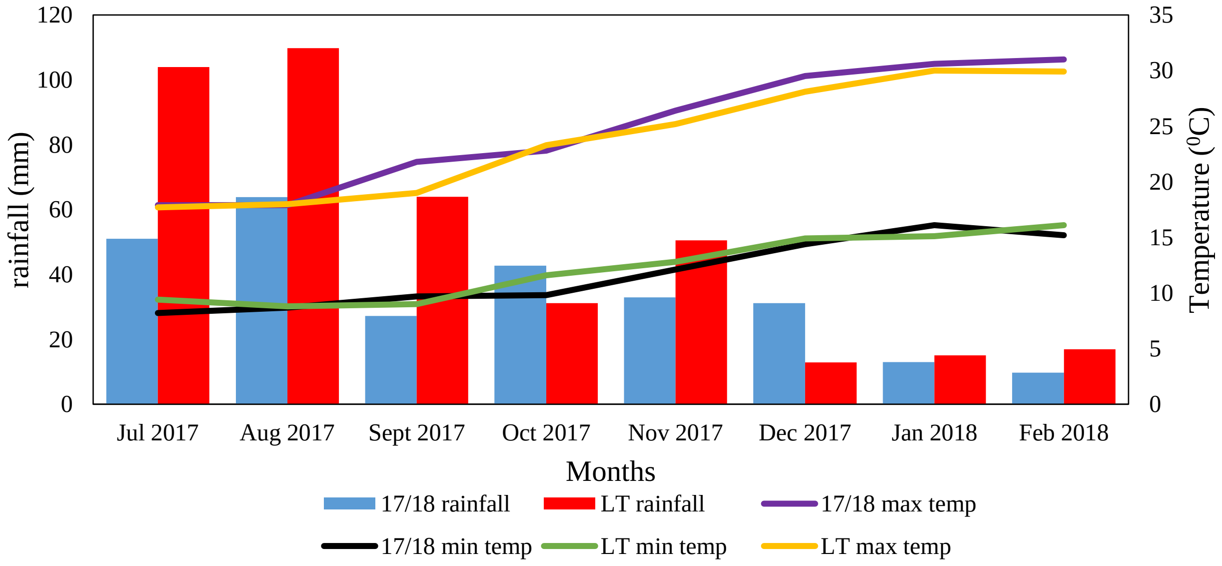


Figure 3.1: Long term (LT) mean rainfall and mean rainfall for 2017/18, as well as the long-term minimum and maximum temperatures, and 2017/2018 minimum and maximum temperatures.

The trial was managed under permanent sprinkler irrigation. Irrigation was scheduled based on soil water potential as reflected by tensiometers with water applied as soon as tensiometer readings at 150 mm soil depth reached -25 kPa. Weed management was done using a combination of hand hoeing and chemical control when the weeds emerged after harvest until the lucerne had full ground cover over the soil surface, with chemical application usually done after harvest if necessary.

3.2 Experimental design and treatments

The study was carried out on 0.945 ha of existing lucerne cultivar trial. It was laid out as a completely randomised block design. There were 15 cultivars seeded on 12 November 2014 at a density of 20 kg ha^{-1} with a row width of 0.3 m using a fine seed planter with tines. Each of the 15 cultivars listed in Table 3.1 was regarded as a treatment and replicated randomly in three blocks. There was a total of 45 experimental plots, with each experimental plot 8 m x 2.1 m in size. Figure 3.2 shows the layout of the experimental area.

Table 3. 1: Lucerne cultivars and their dormancy classes used for the study

Cultivar	Winter activity	Dormancy class
SA standard	Intermediate dormancy	6
Venus	Intermediate dormancy	6
L70	Intermediate dormancy	7
Sardi 70	Intermediate dormancy	7
SA Select	Intermediate dormancy	7
WL 525 HQ	Winter active	8
KKS 9911	Highly winter active	9
ML 99	Highly winter active	10
Sardi 10	Highly winter active	10
WL 711WF	Highly winter active	10
Agsalfa	Highly winter active	10
Alfamastic	Highly winter active	10
WL1111	Highly winter active	11
DM 32192	*	*
Derrick Oudsthoorn	*	*

* Dormancy class not known

3.3 Data collection

Data was collected using the different yield estimation instruments namely, the RPM, ceptometer, meter ruler and UAV. Each yield estimation instrument was then compared to the cut-and-dry method which is the standard way of measuring herbage yield of lucerne. A repeated measure of 12 cuts was supposed to be done during the data collection period to calibrate and test the alternative methods over all seasons, but due to the drought in the Western

Cape, a repeated measure of only seven cuts was done. Harvesting was done when regrowth appeared. - It was done once every 33 days on average. The longest time taken between harvests was 39 days and the shortest time was 28 days.

3.3.1 Cut-and-dry method

The experimental plots were cut using an Agria mower with a cutting bar 1.6 m in length. To eliminate border effects the centre of each plot was harvested and the border rows excluded. The plot fresh weight was recorded infield using a platform scale. Herbage material was cut from each experimental plot (before the Agria mower cut the plots) using three rings of 0.0985 m^2 in size that were randomly placed within the plots and used as grab samples. A cutting shear was used to cut the herbage within the rings to a level of five centimetres above the ground to prevent cutting off the growth points. The herbage material was placed in labelled bags and fresh weight readings were taken and recorded. Dry weight was determined by placing the grab samples in a drying oven for three days at constant temperature of 60°C. Total herbage yield per plot (DM kg ha^{-1}) was calculated using DM content from the grab samples using the formulas:

$$DM\% = (grab\ sample\ dry\ weight(kg)\ \div grab\ sample\ fresh\ weight\ (kg)) \times 100$$

$$DM(kg) = (DM\%\ \div 1000) \times plot\ fresh\ weight$$

$$DM\ kg\ ha^{-1} = (DM(kg) \div plot\ area) \times 10000$$

3.3.2 Rising plate meter

The rising plate meter (RPM) is an instrument used to quantify the amount of pasture using compressed plant height. The RPM is a made up of a plate 0.0985 m^2 with a shaft that goes through the centre of the plate. It takes readings by lowering it vertically on the lucerne with shaft resting on the ground to leave the plate supported by the lucerne. The lucerne height and density will push up the plate up the shaft to the maximum height possible. The height of the lucerne is displayed by the RPM. Twenty RPM readings were randomly taken in a zig-zag pattern of each plot (avoiding the borders). The RPM measures the compressed height with the initial and final height readings recorded. Initial height is the reading when the plate is at rest. Final height is the reading taken once the plate rests after measuring the plant height. The initial compressed height reading was subtracted from the final reading to obtain the total compressed height of each experimental plot. The RPM herbage yield estimations were then calibrated by drawing up regressions of the plant height (cm) with the herbage yield calculated from the cut-and-dry method.

3.3.3 Ceptometer

The ceptometer is an instrument used to measure light interception in the plant canopy and calculate leaf area index (LAI). It has a probe that has 80 independent sensors that measure photosynthetically active radiation (PAR) in the 400-700 nm waveband. To obtain readings the ceptometer probe was placed above the lucerne canopy over 10 different spots across each experimental plot with each reading being taken and recorded. Thirty centimetres from the edge of the plots the ceptometer was inserted below the canopy (to eliminate border effect) to take and record 10 below canopy readings. Light interception was calculated as the difference between above and below canopy readings which was displayed as (μmol m^{-2} s^{-1}). Ceptometer herbage yield estimations were then calibrated by drawing up regressions of light intercepted (μmol m^{-2} s^{-1}) with the herbage yield calculated from the cut-and-dry method.

3.3.4 Meter ruler

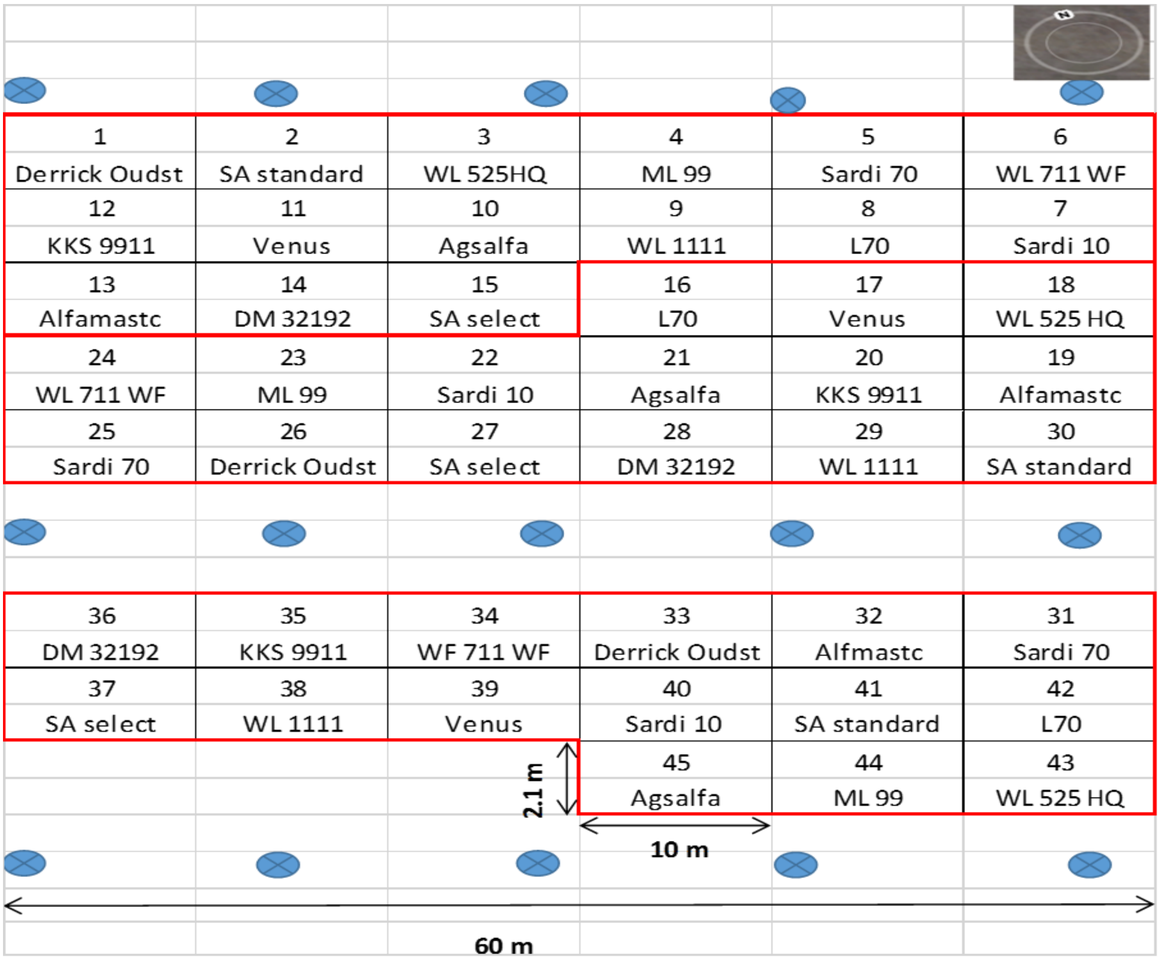
The meter ruler is a graduated pole used to measure plant height in the field. It is a simple and practical tool used to quickly estimate herbage yield by relating it to plant height. Readings for this trial were taken in a zig zag pattern in each experimental plot. The meter ruler was placed vertically on the ground against the lucerne and the reading was taken off the tip of the lucerne. Ten measurements were taken per experimental plot and the mean calculated. Each reading recorded as plant height (cm) was then used to calibrate meter ruler herbage yield estimations by drawing up regression of the plant height (cm) with the herbage yield calculated from the cut-and-dry method.

3.3.5 Unmanned Aerial Vehicle

An Iris quadcopter with GoPro Hero 4 Silver camera retrofitted with 5.4 mm lens was used to capture aerial images of the lucerne. The flight was programmed in tower from 3DR at a height of 20 m with vertical and horizontal overlap at two-second intervals at 800 x 600 dpi. Each flight was approximately 3 minutes each. The images were converted to produce the amount of canopy cover (%) which was then used to calibrate UAV percentage cover with herbage yield calculated from the cut-and-dry. Due to unavailability of the UAV on some of the harvesting dates, or windy conditions, data collection using the UAV was limited to only four cuts.

3.4 Statistical analyses

Statistical analyses were performed using STATISTICA version 13 (Dell Inc. 2016). A repeated measure ANOVA was done to test for pasture production through time. Fixed effects specified as linear time, treatment and their interaction were also tested. Residuals were tested for normality and homogeneity of variance. A general regression model was drawn up and used to find the correlation between herbage yield and the respective yield estimation instruments. The Bonferroni and Fisher's least significant differences (LSD) test was conducted at a 5% significance level to determine whether interactions among the three factors of interest were significant.



1 Derrick Oudst	2 SA standard	3 WL 525HQ	4 ML 99	5 Sardi 70	6 WL 711 WF
12 KKS 9911	11 Venus	10 Agsalfa	9 WL 1111	8 L70	7 Sardi 10
13 Alfamastc	14 DM 32192	15 SA select	16 L70	17 Venus	18 WL 525 HQ
24 WL 711 WF	23 ML 99	22 Sardi 10	21 Agsalfa	20 KKS 9911	19 Alfamastc
25 Sardi 70	26 Derrick Oudst	27 SA select	28 DM 32192	29 WL 1111	30 SA standard
36 DM 32192	35 KKS 9911	34 WF 711 WF	33 Derrick Oudst	32 Alfmastc	31 Sardi 70
37 SA select	38 WL 1111	39 Venus	40 Sardi 10	41 SA standard	42 L70
			45 Agsalfa	44 ML 99	43 WL 525 HQ

Figure 3.2: Layout of the experimental plots. Blue circles indicate the position of the irrigation sprinklers. The red lines indicate the outline of the three different blocks.

Chapter 4: Results

The results presented in this chapter focus on herbage yield and the data collected from the different yield estimation instruments namely RPM, ceptometer, meter ruler and UAV. Regressions were calculated to show correlations of different instruments estimating herbage yield to the actual herbage yield. Multiple regressions were also conducted to show interactions between the RPM, ceptometer and meter ruler.

4.1 Herbage yield production

For herbage yield, the interaction between cultivar and the cutting date was not significant ($p>0.05$) and therefore main effects for cultivar and cutting date are shown. Mean herbage yield production was compiled for all cultivars from January 2015 up to February 2018 (Figure 4.1). Cultivar WL 525HQ produced the highest mean annual herbage yield of 2411.49 kg DM ha^{-1} but did not differ ($p<0.05$) from six other cultivars (shown in grey in Figure 4.1). Cultivar Venus (shown in green in Figure 4.1) produced the lowest yield and was the worst performing together with Agsalfa, Sardi 10 and KKS 9911 (shown in brown in Figure 4.1).

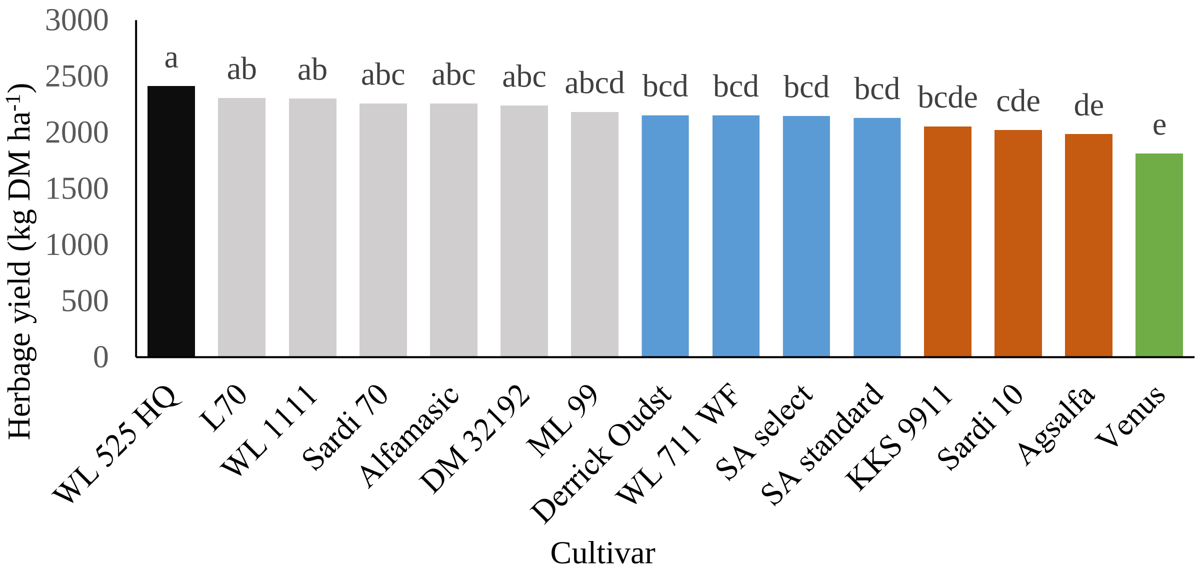


Figure 4.1: Mean herbage yield for cultivars from 2015 to 2018. Bars with different colours indicate significant differences ($p<0.05$).

Herbage yields per cutting date are displayed in Figure 4.2. Herbage yield production was high during the warm months of the year (December, January, and February). In December 2015, herbage yield production was highest at 3761 kg DM ha^{-1} ($p<0.05$) (shown in black in Figure 4.2). During the winter months of July and August herbage yield production was at its lowest.

July 2015 and July 2017 (shown in green in Figure 4.2) herbage yield production was lowest at 1143 kg DM ha^{-1} and 1003 kg DM ha^{-1} respectively. Between May 2016 and July 2017 there was no herbage yield data collected.

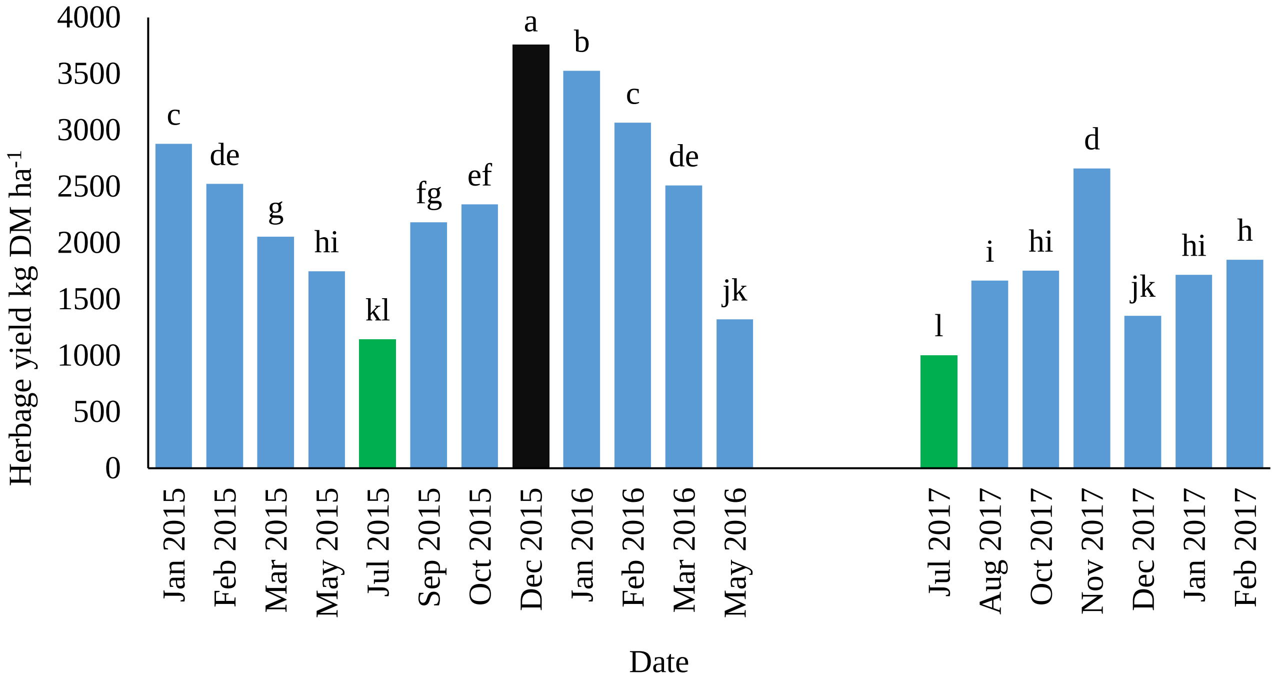


Figure 4.2: Mean herbage yield per cutting date from 2015 to 2018. Bars with different colours indicate significant differences ($p<0.05$)

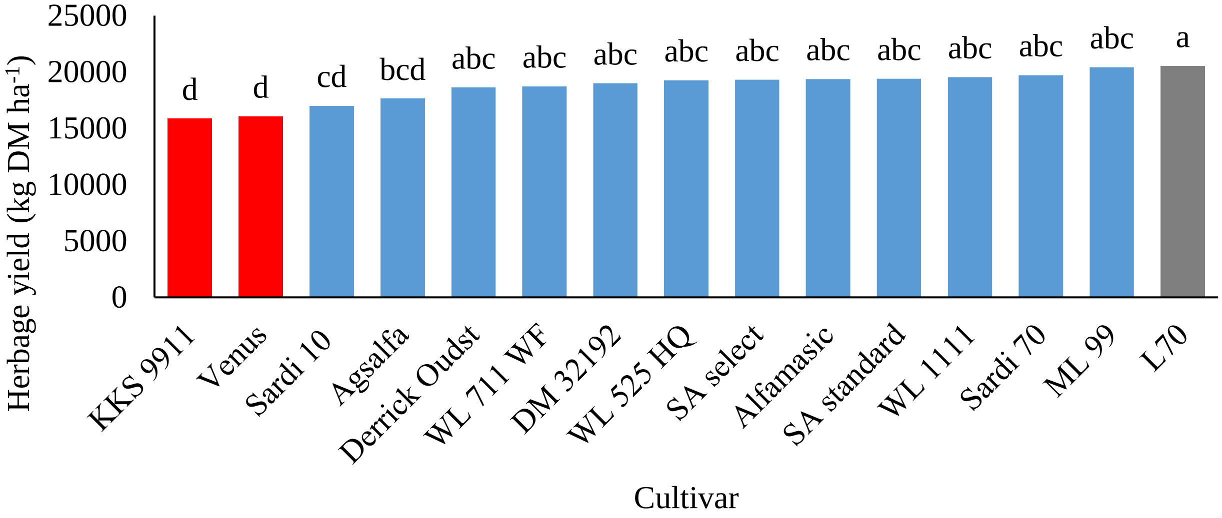


Figure 4.3: Herbage yield per cultivar for 2015. The different letters above the bars indicate significant differences ($p<0.05$).

Table 4.3 displays herbage yield performance by cultivar over the year 2015. Cultivar L70 (coloured in grey in Figure 4.3) produced the highest average annual herbage yield but did not differ ($p<0.05$) from the next ten cultivars as shown in Figure 4.3. KKS 9911 and Venus were the lowest in herbage yield production (coloured in red in Figure 4.3) and did not differ ($p<0.05$) with Sardi 10 and Agsalfa which also produced the low yields.

4.2 RPM, ceptometer, meter ruler regressions

Table 4.1 and Figure 4.4 displays the different regressions for the three yield estimation models over the entire period of data collection (July 2017 to February 2018). Linear and quadratic regressions were compared. The RPM had good yield estimations with a linear regression ($r^2 = 0.69$), which was significant ($p<0.05$), whilst the quadratic regression had a lower coefficient of determination ($r^2 = 0.54$; $p<0.05$). For the ceptometer, linear regression had a significant coefficient of determination of $r^2 = 0.50$, while the quadratic regression was not significant. The meter ruler had moderate accuracy $r^2 = 0.55$, ($p<0.05$) when linear regression was used, whilst the quadratic regression was lower at $r^2 =0.33$ ($p<0.05$). The RPM had the best yield estimation compared to the ceptometer and meter ruler. Overall, the linear regressions proved to provide more accurate regressions compared to the quadratic regressions when all dates are considered.

Table 4.1: Correlations for linear and quadratic regressions between actual lucerne herbage yield and three indirect methods of estimating yield. * ns indicates value was not significant

Estimation method	r^2 for linear equation	p-value	r^2 for quadratic equation	p-value
Rising plate meter	0.69	<0.001	0.54	<0.001
Ceptometer	0.50	<0.001	0.26	ns
Meter ruler	0.55	<0.001	0.33	<0.001

4.3 Monthly RPM regressions

The generalised predictive regressions that were generated for the RPM for each individual month is displayed in Table 4.2 and Figure 4.5. The regressions were a comparison of linear and quadratic regressions. Quadratic and linear correlations were drawn as a comparison to show which provided more accurate coefficients of determination. For July 2017, the linear regression had a better coefficient of determination $r^2 = 0.63$ ($p<0.05$) compared to quadratic regression which was not significant. For August 2017, the linear regression had a significant coefficient of determination of $r^2 = 0.63$ and quadratic regression was not significant. In October linear regression had a good coefficient of determination $r^2 = 0.61$ ($p<0.05$) as compared to quadratic regression that was not significant. November 2017 coefficients of determination for both linear and quadratic equations were low and not significant. In December 2017, the linear and quadratic coefficients of determination provided the most accurate estimations compared to all cuts with linear providing a significant coefficient of determination of $r^2 = 0.90$. The quadratic regression coefficient of regression was, however, not significant. In January 2018, the yield estimation accuracy with a linear regression coefficient of determination was $r^2 = 0.81$ ($p<0.05$) and the quadratic regression was not significant. For February 2018, linear regression produced a moderate coefficient of determination of $r^2 = 0.53$ ($p<0.05$) whilst quadratic produced $r^2 = 0.59$ ($p<0.05$).

Table 4.2: Monthly correlations for linear and quadratic regressions between actual lucerne herbage yield and RPM method of estimating yield. * ns indicates value was not significant

Month	r^2 for linear equation	p-value	r^2 for quadratic equation	p-value
July 2017	0.63	<0.001	0.44	ns
August 2017	0.63	<0.001	0.40	ns
October 2017	0.61	<0.001	0.05	ns
November 2017	-0.29	ns	0.09	ns
December 2017	0.90	0.050	0.84	ns
January 2018	0.81	<0.001	0.68	ns
February 2018	0.53	<0.001	0.59	<0.05

4.4 Monthly ceptometer regressions

The generalised predictive regressions that were generated for the ceptometer for each individual month is displayed in Table 4.3 and Figure 4.6. The regressions were a comparison of linear and quadratic equations to show which provided a more accurate coefficient of determination. For July 2017, the linear regressions had a better coefficient of determination $r^2 = 0.50$ ($p<0.05$), with quadratic regression having a higher coefficient of determination albeit not significant. For August 2017, linear regression had a significant coefficient of determination of $r^2 = 0.77$ and quadratic regression was not significant. In October 2017 coefficients of determination were poor, but significant at $r^2 = 0.42$ for the linear regression whilst not significant for the quadratic regression. November 2017 coefficients of determination for both linear and quadratic were not significant. December 2017 had the best coefficients of determination for ceptometer measurements. Linear regression had an r^2 of 0.81

($p<0.05$), whilst the quadratic regression was not significant. For January 2018 the regressions produced a coefficient of determination for linear regression at $r^2 = 0.68$ ($p<0.05$) whilst the quadratic regression was not significant. February 2018 coefficient of determination was average for the linear regression $r^2 = 0.56$ ($p<0.05$), whilst the quadratic regression was not significant.

Table 4.3: Monthly correlations for linear and quadratic regressions between actual lucerne herbage yield and ceptometer method of estimating yield. * ns indicates value was not significant

Month	r^2 for linear equation	*p*-value	r^2 for quadratic equation	*p*-value
July 2017	0.50	<0.001	0.61	ns
August 2017	0.77	0.028	0.13	ns
October 2017	0.42	0.004	0.20	ns
November 2017	0.09	ns	0.12	ns
December 2017	0.81	<0.001	0.73	ns
January 2018	0.68	<0.001	0.47	ns
February 2018	0.56	<0.001	0.33	ns

4.5 Monthly meter ruler regressions

The generalised predictive regressions that were generated for the meter ruler for each individual month is displayed in Table 4.4 and Figure 4.7. The regressions were a comparison of linear and quadratic equations to show which provided more accurate coefficients of determination. For July 2017 the linear regression had a coefficient of determination $r^2 = 0.55$ ($p<0.05$), whilst there was a poor coefficient of determination for quadratic regression at $r^2 = 0.30$ that was not significant. August 2017 the linear regression gave a coefficient of determination of $r^2=0.80$ ($p<0.05$) with quadratic regression not significant. October 2017 had poor coefficients of determination with linear regression at $r^2 = 0.38$ ($p<0.05$) and quadratic regression that was not significant. November 2017 there were poor coefficients of determination which were both not significant for linear and quadratic regressions. December 2017 the coefficients of determination were at the highest for the meter ruler with linear regression at $r^2 = 0.90$ ($p<0.05$) whilst the quadratic regression was not significant. January 2018 produced a significant coefficient of determination with linear regression at $r^2 = 0.72$ with quadratic regression not significant. For February 2018 linear regression produced a coefficient of determination at $r^2 = 0.70$ ($p<0.05$) and quadratic regression the coefficient of determination was not significant.

Table 4.4: Monthly correlations for linear and quadratic regressions between actual lucerne herbage yield and meter ruler method of estimating yield. * ns indicates value was not significant

Month	r^2 for linear equation	p-value	r^2 for quadratic equation	p-value
July 2017	0.55	<0.001	0.30	ns
August 2017	0.80	<0.001	0.65	ns
October 2017	0.38	0.010	0.15	ns
November 2017	0.11	ns	0.13	ns
December 2017	0.90	<0.001	0.83	ns
January 2018	0.72	<0.001	0.52	ns
February 2018	0.70	<0.001	0.49	ns

4.6 Monthly UAV regressions

The generalised predictive regressions that were generated for the UAV for each individual month is displayed in Table 4.5 and Figure 4.8. Data was collected for four cuts. For all cuts combined the linear regression produced a coefficient of determination of $r^2 = 0.45$ ($p<0.05$) and the quadratic regression was also significant with a poor coefficient of determination $r^2 = 0.26$. For July 2017 the linear regression produced a good coefficient of determination of $r^2 = 0.72$ ($p<0.05$) whilst linear regression was not significant. August 2017 linear regression produced a coefficient of determination of $r^2 = 0.65$ ($p<0.05$) with the quadratic regression not significant. October the regressions produced coefficients of determination which were not significant for the linear and quadratic regressions. For December 2017 the linear regression produced a good coefficient of determination $r^2 = 0.66$ ($p<0.05$) and quadratic regression that was not significant.

4.7 Multiple regressions for RPM, ceptometer and meter ruler

Multiple regressions were calculated for all the cuts combined and the individual cuts of the three different instruments (RPM, ceptometer and meter ruler). For all the cuts combined the different permutations are displayed in Table 4.6. The three yield estimation models (RPM, ceptometer and meter ruler) had multiple regression with a coefficient of determination of $r^2 = 0.49$. The beta coefficients of the RPM and ceptometer were significant at 0.66 and 0.15, respectively. The RPM and ceptometer produced a coefficient of determination of $r^2 = 0.49$, with the RPM giving 0.61 ($p<0.05$) and the ceptometer = 0.13 ($p<0.05$) beta coefficients respectively. The RPM and meter ruler together had a coefficient of determination of $r^2 = 0.48$ with the RPM giving a beta coefficient or 0.69 ($p<0.05$). The interaction between the ceptometer and meter ruler produced a coefficient of determination of $r^2 = 0.33$. Beta coefficients for the ceptometer was 0.24 ($p<0.05$) and the meter ruler was 0.39 ($p<0.05$).

Table 4.5: Monthly correlations for linear and quadratic regressions between actual lucerne herbage yield and UAV method of estimating yield. * ns indicates value was not significant

Month	r^2 for linear equation	*p*-value	r^2 for quadratic equation	*p*-value
All cuts	0.45	<0.001	0.26	<0.001
July	0.72	<0.001	0.57	ns
August	0.65	<0.001	0.47	ns
October	0.19	ns	0.52	ns
December	0.66	<0.001	0.51	ns

Table 4.6: Multiple regression summary for different permutations of the RPM, ceptometer and meter ruler. * indicates value was significant

Yield Estimation instrument	**Beta coefficient**	**r^2**
RPM	0.66*	0.49
Ceptometer	0.15*	
Meter ruler	-0.07	
Ceptometer	0.13*	0.49
RPM	0.61*	
RPM	0.69*	0.48
Meter ruler	0.01	
Ceptometer	0.24*	0.33
Meter ruler	0.39*	

Table 4.7 displays the different permutations for the multiple regressions for July 2017. The three yield estimation models (RPM, ceptometer and meter ruler) had multiple regression with a coefficient of determination of $r^2 = 0.63$. The ceptometer beta coefficient was 0.59 ($p<0.05$). The RPM and ceptometer produced a coefficient of determination of $r^2 = 0.63$ with the ceptometer giving a 0.63 ($p<0.05$) beta coefficient. The RPM and meter ruler together had a coefficient of determination of $r^2 = 0.45$ with the RPM giving a beta coefficient of 0.47 ($p<0.05$) and the meter ruler 0.028 ($p<0.05$). The interaction between the ceptometer and meter ruler

produced a coefficient of determination of $r^2 = 0.62$. The ceptometer had a beta coefficient of 0.68 ($p<0.05$).

Table 4.7: Multiple regression summary for different permutations of the RPM, ceptometer and meter ruler for the month of July 2017. * indicates value was significant

Yield Estimation instrument	**Beta coefficient**	**r^2**
RPM	0.16	0.63
Ceptometer	0.59*	
Meter ruler	0.14	
Ceptometer	0.63*	0.63
RPM	0.21*	
RPM	0.47*	0.45
Meter ruler	0.28*	
Ceptometer	0.68*	0.62
Meter ruler	0.19	

Table 4.8 displays the different permutations for the multiple regressions for August 2017. The three yield estimation models (RPM, ceptometer and meter ruler) had multiple regression with a coefficient of determination of $r^2 = 0.65$. The meter ruler beta coefficient was 0.74 ($p<0.05$). The RPM and ceptometer produced a coefficient of determination of $r^2 = 0.43$ with the RPM giving a 0.59 ($p<0.05$) beta coefficient. The RPM and meter ruler together had a coefficient of determination of $r^2 = 0.64$ with the meter ruler giving a beta coefficient of 0.76 ($p<0.05$). The interaction between the ceptometer and meter ruler produced a coefficient of determination of $r^2 = 0.65$. The ceptometer had a beta coefficient of 0.78 ($p<0.05$).

Table 4.8: Multiple regression summary for different permutations of the RPM, ceptometer and meter ruler for the month of August 2017. * indicates value was significant

Yield Estimation instrument	**Beta coefficient**	**r^2**
RPM	0.05	0.65
Ceptometer	0.08	
Meter ruler	0.74*	
Ceptometer	0.59*	0.43
RPM	0.18	
RPM	0.05	0.64
Meter ruler	0.78*	
Ceptometer	0.78*	0.65
Meter ruler	0.08	

Table 4.9 displays the different permutations for the multiple regressions for October 2017. The three yield estimation models (RPM, ceptometer and meter ruler) had multiple regression with a coefficient of determination of $r^2 = 0.26$. The ceptometer beta coefficient was 0.40 ($p<0.05$). The RPM and ceptometer produced a coefficient of determination of $r^2 = 0.20$ with the ceptometer giving a 0.50 ($p<0.05$) beta coefficient. The RPM and meter ruler together had a coefficient of determination of $r^2 = 0.14$ with the meter ruler giving a beta coefficient of 0.38 ($p<0.05$). The interaction between the ceptometer and meter ruler produced a coefficient of determination of $r^2 = 0.24$. The meter ruler had a beta coefficient of 0.33 ($p<0.05$).

Table 4.9: Multiple regression summary for different permutations of the RPM, ceptometer and meter ruler for the month of October 2017. * indicates value was significant

Yield Estimation instrument	**Beta coefficient**	**r^2**
RPM	-0.17	0.26
Ceptometer	0.40*	
Meter ruler	0.28	
Ceptometer	0.50*	0.20
RPM	-0.16	
RPM	0.05	0.14
Meter ruler	0.38*	
Ceptometer	0.26	0.24
Meter ruler	0.33*	

Table 4.10 displays the different permutations for the multiple regressions for November 2017. The three yield estimation models (RPM, ceptometer and meter ruler) had multiple regression with a coefficient of determination of $r^2 = 0.22$. The beta coefficients for the RPM and meter ruler were -0.56 ($p<0.05$) and 0.040 ($p<0.05$) respectively. The RPM and ceptometer produced a coefficient of determination of $r^2 = 0.12$ with the RPM giving a -0.35 ($p<0.05$) beta coefficient. The RPM and meter ruler together had a coefficient of determination of $r^2 = 0.21$ with the RPM giving a beta coefficient of -0.56 ($p<0.05$) and the meter ruler 0.44 ($p<0.05$). The interaction between the ceptometer and meter ruler produced a coefficient of determination of $r^2 = 0.14$ and no significant beta coefficient.

Table 4.10: Multiple regression summary for different permutations of the RPM, ceptometer and meter ruler for the month of November 2017. * indicates value was significant

Yield Estimation instrument	Beta coefficient	r^2
RPM	-0.56*	0.22
Ceptometer	0.08	
Meter ruler	0.40	
Ceptometer	0.19	0.12
RPM	-0.35*	
RPM	-0.56*	0.21
Meter ruler	0.44*	
Ceptometer	0.08	0.14
Meter ruler	0.06	

Table 4.11 displays the different permutations for the multiple regressions for December 2017. The three yield estimation models (RPM, ceptometer and meter ruler) had multiple regression with a coefficient of determination of $r^2 = 0.84$. The RPM beta coefficient was 0.45 ($p<0.05$). The RPM and ceptometer produced a coefficient of determination of $r^2 = 0.82$ with the RPM giving a 0.78 ($p<0.05$) beta coefficient. The RPM and meter ruler together had a coefficient of determination of $r^2 = 0.83$ with the RPM giving a beta coefficient of 0.47 ($p<0.05$) and the meter ruler 0.46 ($p<0.05$). The interaction between the ceptometer and meter ruler produced a coefficient of determination of $r^2 = 0.82$ the meter ruler had a beta coefficient of 0.82 ($p<0.05$).

Table 4.11: Multiple regression summary for different permutations of the RPM, ceptometer and meter ruler for the month of December 2017. * indicates value was significant

Yield Estimation instrument	Beta coefficient	r^2
RPM	0.45*	0.84
Ceptometer	0.06	
Meter ruler	0.41	
Ceptometer	0.15	0.82
RPM	0.78*	
RPM	0.47*	0.83
Meter ruler	0.46*	
Ceptometer	0.10	0.82
Meter ruler	0.82*	

Table 4.12 displays the different permutations for the multiple regressions for January 2018. The three yield estimation models (RPM, ceptometer and meter ruler) had multiple regression with a coefficient of determination of $r^2 = 0.82$. The RPM beta coefficient was 0.54 ($p<0.05$) and ceptometer 0.38 ($p<0.05$). The RPM and ceptometer interaction produced a coefficient of determination of $r^2 = 0.79$ with the RPM giving a 0.64 ($p<0.05$) beta coefficient and the

ceptometer a 0.39 ($p<0.05$) beta coefficient. The RPM and meter ruler interaction together had a coefficient of determination of $r^2 = 0.69$ with the RPM giving a beta coefficient of 0.65 ($p<0.05$). The interaction between the ceptometer and meter ruler produced a coefficient of determination of $r^2 = 0.68$ the meter ruler had a beta coefficient of 0.52 ($p<0.05$) and the ceptometer had a 0.45 ($p<0.05$) beta coefficient.

Table 4.12: Multiple regression summary for different permutations of the RPM, ceptometer and meter ruler for the month of January 2018. * indicates value was significant

Yield Estimation instrument	**Beta coefficient**	**r^2**
RPM	0.54*	0.82
Ceptometer	0.38*	
Meter ruler	0.14	
Ceptometer	0.39*	0.79
RPM	0.64*	
RPM	0.65*	0.69
Meter ruler	0.22	
Ceptometer	0.45*	0.68
Meter ruler	0.52*	

Table 4.13 displays the different permutations for the multiple regressions for February 2018. The three yield estimation models (RPM, ceptometer and meter ruler) had multiple regression with a coefficient of determination of $r^2 = 0.52$. The meter ruler beta coefficient was 0.52 ($p<0.05$). The RPM and ceptometer interaction produced a coefficient of determination of $r^2 = 0.39$ with the RPM giving a 0.32 ($p<0.05$) beta coefficient and the ceptometer a 0.39 ($p<0.05$) beta coefficient. The RPM and meter ruler interaction together had a coefficient of determination of $r^2 = 0.50$ with the RPM giving a beta coefficient of 0.61 ($p<0.05$). The interaction between the ceptometer and meter ruler produced a coefficient of determination of $r^2 = 0.51$ the meter ruler had a beta coefficient of 0.59.

Table 4.13: Multiple regression summary for different permutations of the RPM, ceptometer and meter ruler for the month of February 2018. * indicates value was significant

Yield Estimation instrument	**Beta coefficient**	**r^2**
RPM	0.09	0.52
Ceptometer	0.19	
Meter ruler	0.52*	
Ceptometer	0.39*	0.39
RPM	0.32*	
RPM	0.14	0.50
Meter ruler	0.61*	
Ceptometer	0.21	0.51
Meter ruler	0.59*	

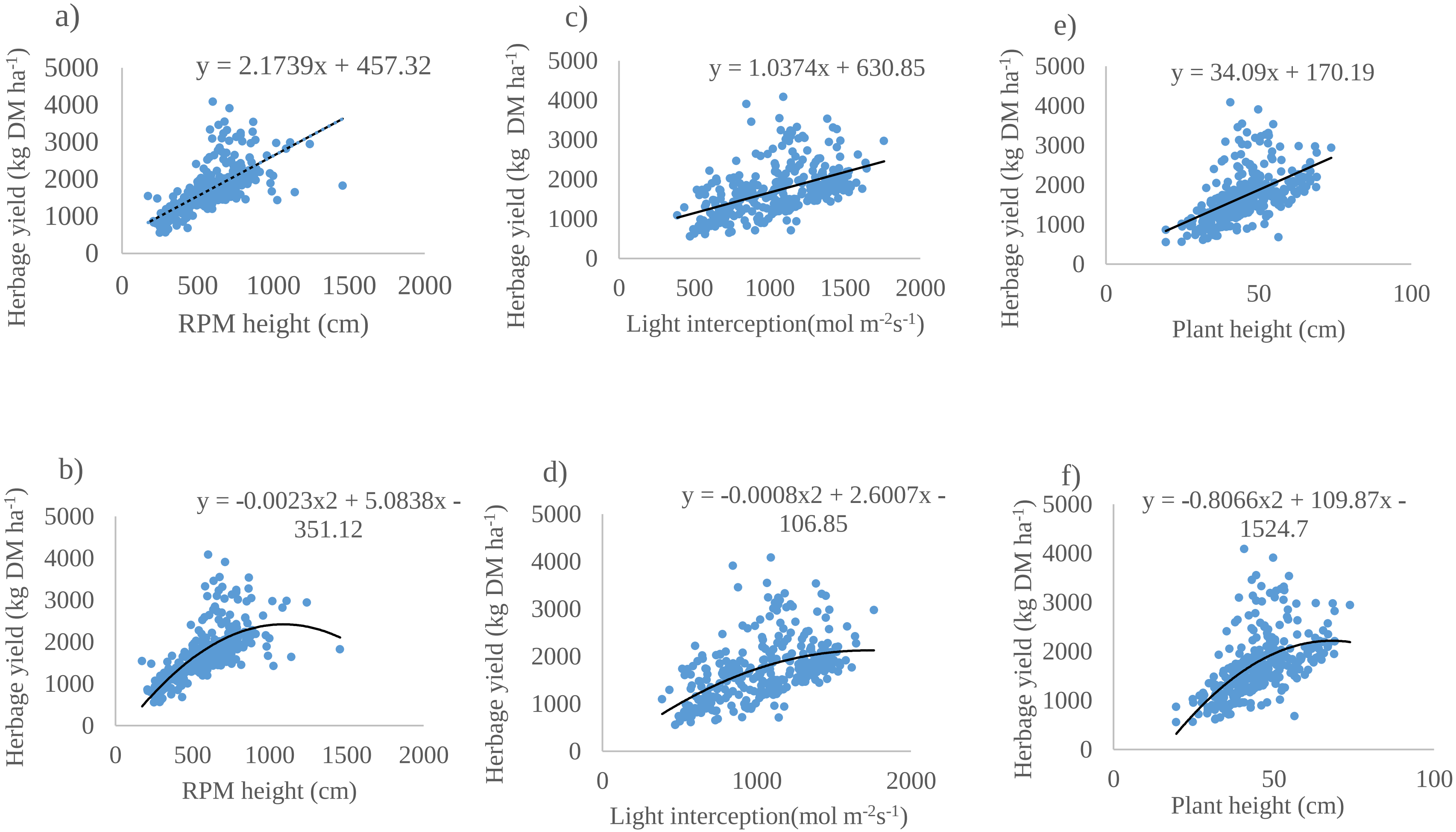
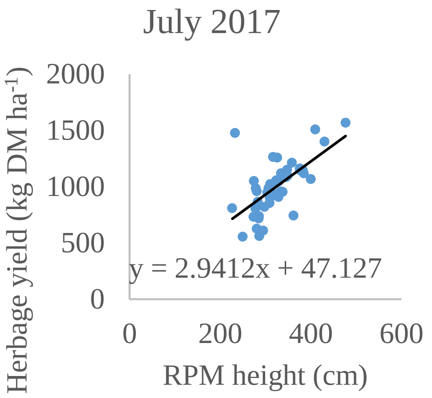
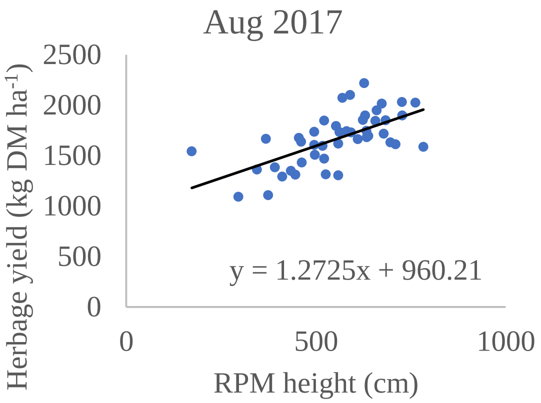
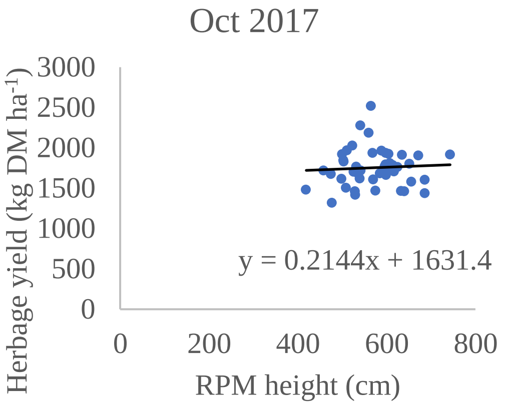
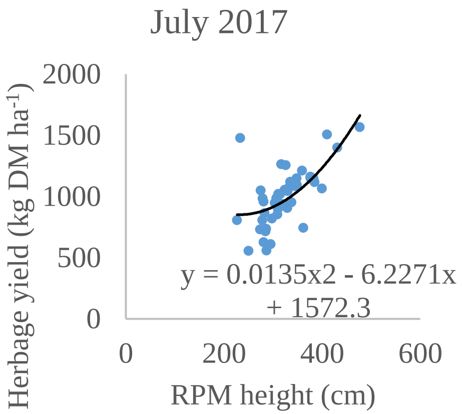


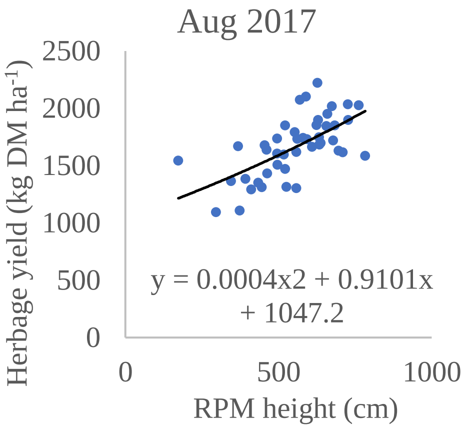
Figure 4.4: Overall linear and quadratic regressions for the three different yield estimation techniques (rising plate meter, ceptometer and meter ruler) on herbage yield estimation of lucerne. Dots scattered closer to the trendline show more accuracy of the regression in estimating lucerne yield

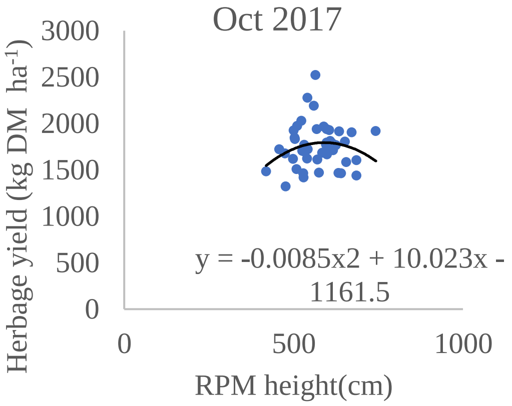

July 2017
Herbage yield (kg DM ha^{-1})
2000
1500
1000
500
0
y = 2.9412x + 47.127
0
200
400
600
RPM height (cm)


Aug 2017
Herbage yield (kg DM ha^{-1})
2500
2000
1500
1000
500
0
y = 1.2725x + 960.21
0
500
1000
RPM height (cm)


Oct 2017
Herbage yield (kg DM ha^{-1})
3000
2500
2000
1500
1000
500
0
y = 0.2144x + 1631.4
0
200
400
600
800
RPM height (cm)


July 2017
Herbage yield (kg DM ha^{-1})
2000
1500
1000
500
0
y = 0.0135x2 - 6.2271x + 1572.3
0
200
400
600
RPM height (cm)


Aug 2017
Herbage yield (kg DM ha^{-1})
2500
2000
1500
1000
500
0
y = 0.0004x2 + 0.9101x + 1047.2
0
500
1000
RPM height (cm)


Oct 2017
Herbage yield (kg DM ha^{-1})
3000
2500
2000
1500
1000
500
0
y = -0.0085x2 + 10.023x - 1161.5
0
500
1000
RPM height(cm)

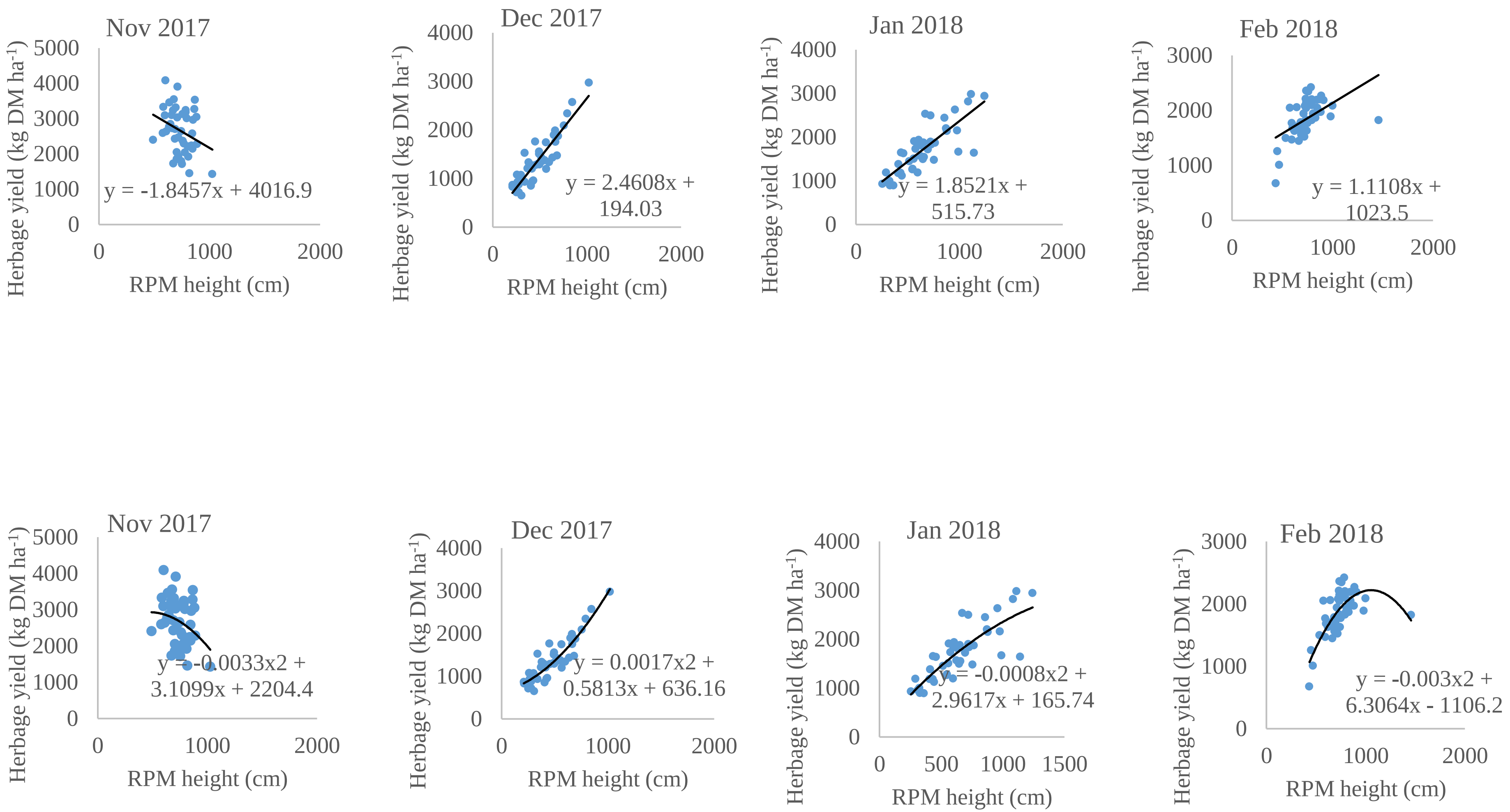
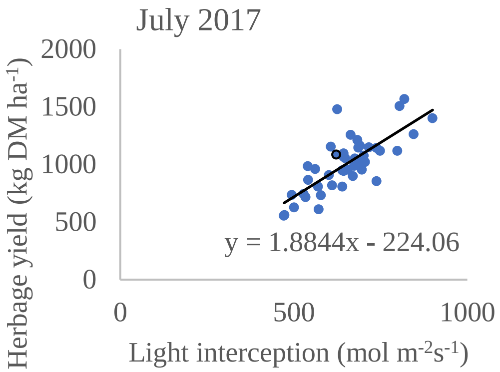
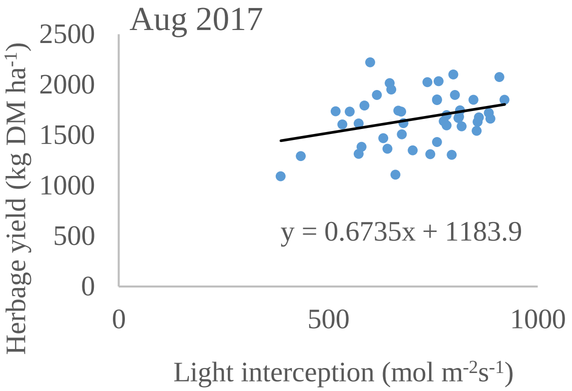
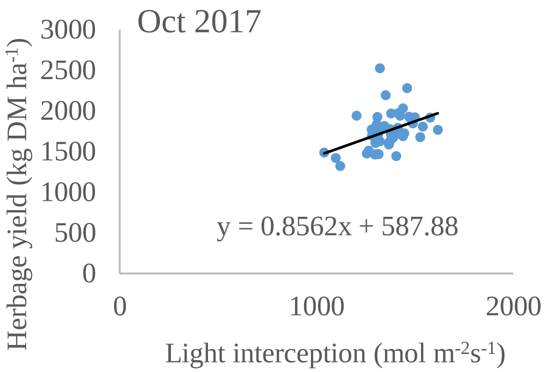
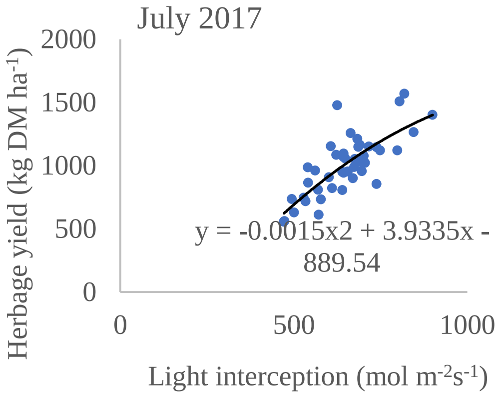


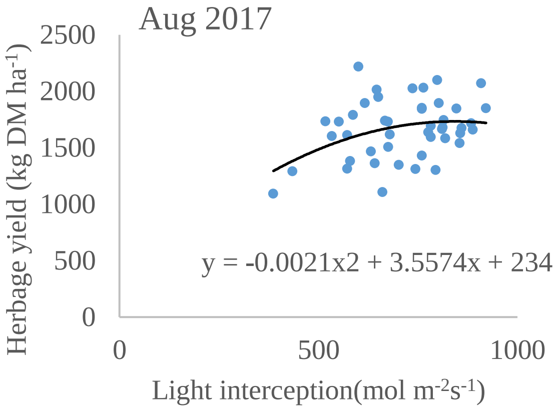
Figure 4.5: Monthly linear and quadratic rising plate meter regressions for herbage yield estimation using the rising plate meter. Dots scattered closer to the trendline show more accuracy of the regression in estimating lucerne yield

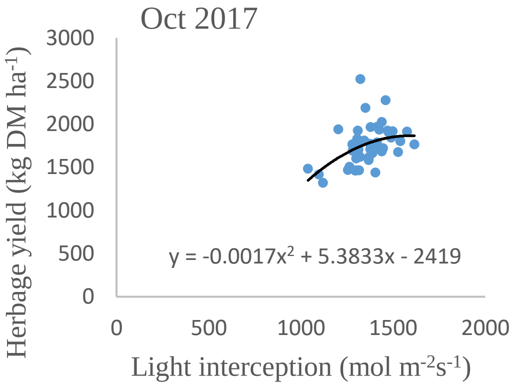

July 2017
Herbage yield (kg DM ha-1)
2000
1500
1000
500
0
y = 1.8844x - 224.06
0
500
1000
Light interception (mol m-2s-1)


Aug 2017
Herbage yield (kg DM ha-1)
2500
2000
1500
1000
500
0
y = 0.6735x + 1183.9
0
500
1000
Light interception (mol m-2s-1)


Oct 2017
Herbage yield (kg DM ha-1)
3000
2500
2000
1500
1000
500
0
y = 0.8562x + 587.88
0
1000
2000
Light interception (mol m-2s-1)


July 2017
Herbage yield (kg DM ha-1)
2000
1500
1000
500
0
y = -0.0015x2 + 3.9335x - 889.54
0
500
1000
Light interception (mol m-2s-1)


Aug 2017
Herbage yield (kg DM ha-1)
2500
2000
1500
1000
500
0
y = -0.0021x2 + 3.5574x + 234
0
500
1000
Light interception(mol m-2s-1)


Oct 2017
Herbage yield (kg DM ha-1)
3000
2500
2000
1500
1000
500
0
y = -0.0017x2 + 5.3833x - 2419
0
500
1000
1500
2000
Light interception (mol m-2s-1)

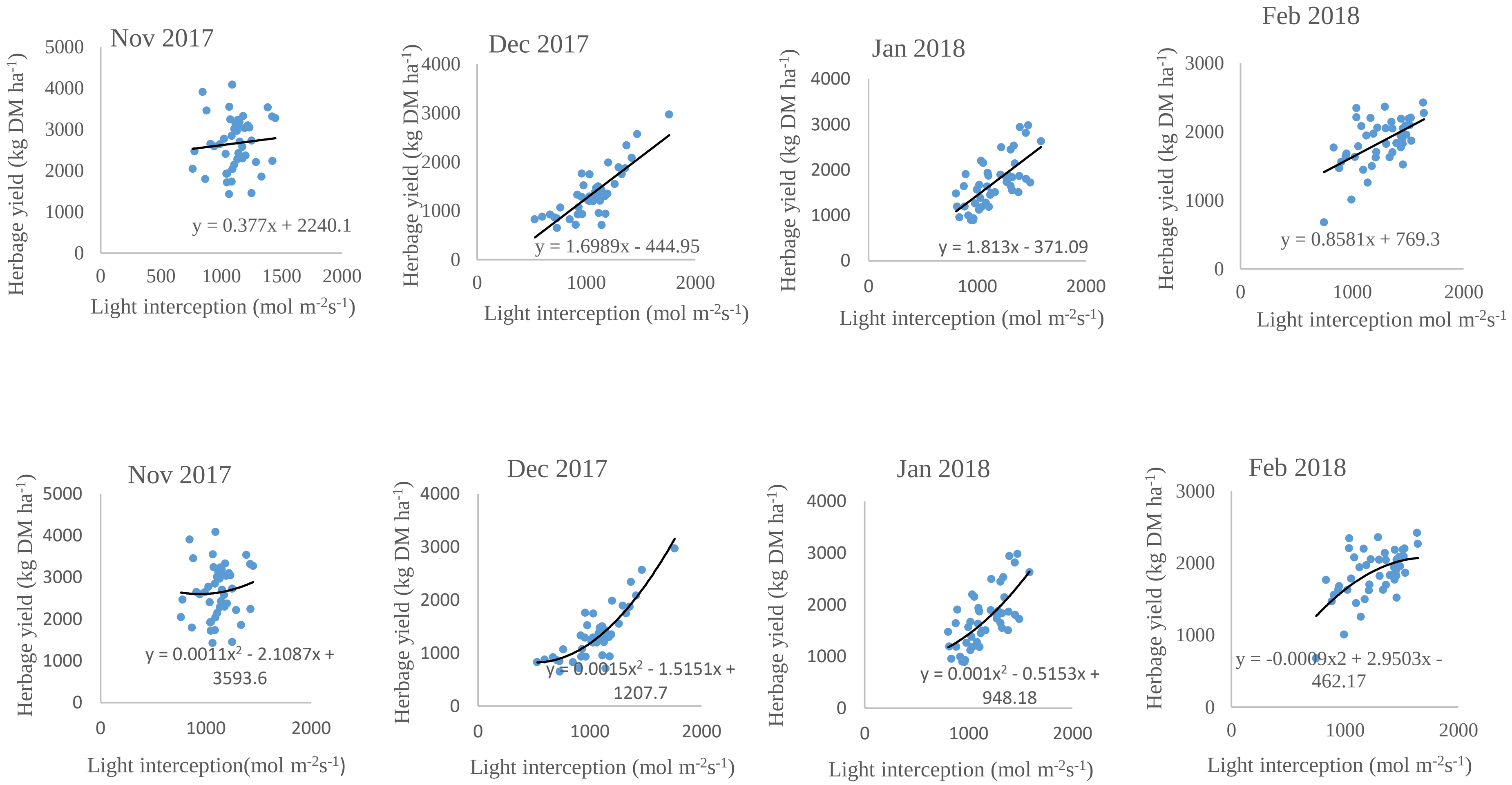
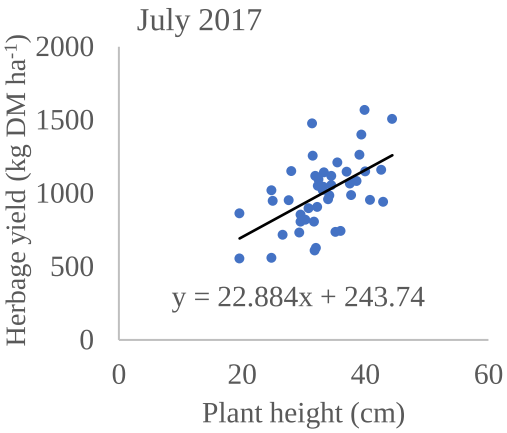
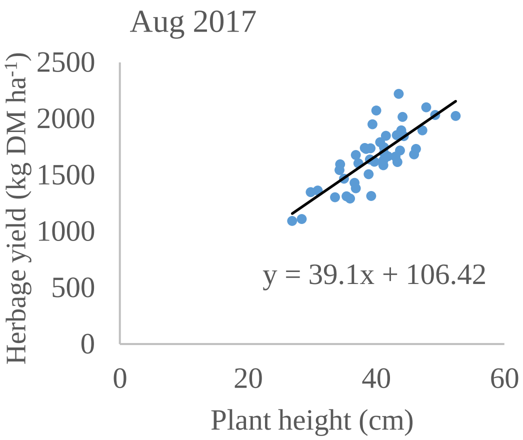
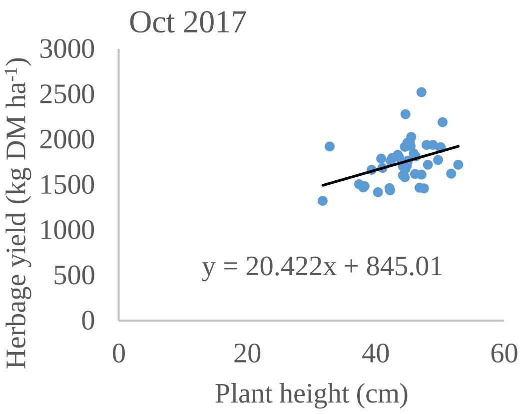
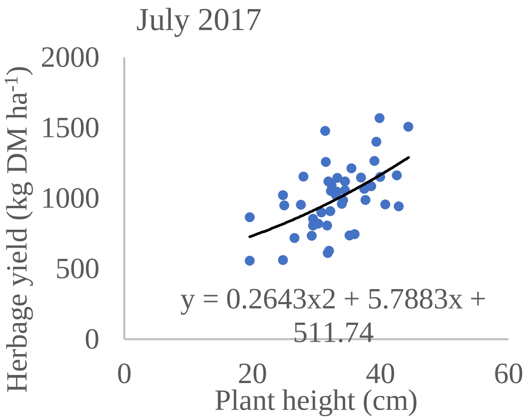


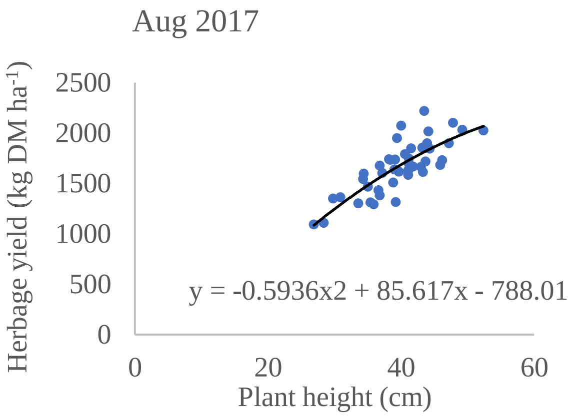
Figure 4.6: Monthly linear and quadratic ceptometer regressions for herbage yield estimation using the ceptometer. Dots scattered closer to the trendline show more accuracy of the regression in estimating lucerne yield

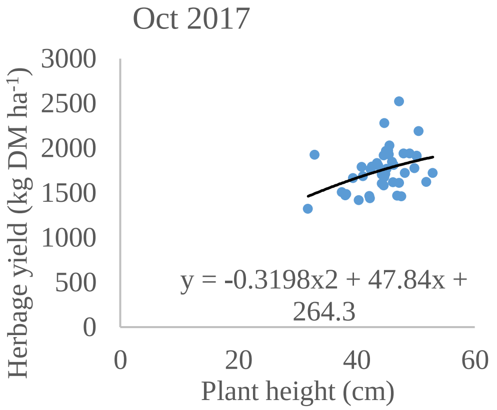

July 2017
Herbage yield (kg DM ha^{-1})
2000
1500
1000
500
0
y = 22.884x + 243.74
0
20
40
60
Plant height (cm)


Aug 2017
Herbage yield (kg DM ha^{-1})
2500
2000
1500
1000
500
0
y = 39.1x + 106.42
0
20
40
60
Plant height (cm)


Oct 2017
Herbage yield (kg DM ha^{-1})
3000
2500
2000
1500
1000
500
0
y = 20.422x + 845.01
0
20
40
60
Plant height (cm)


July 2017
Herbage yield (kg DM ha^{-1})
2000
1500
1000
500
0
y = 0.2643x2 + 5.7883x + 511.74
0
20
40
60
Plant height (cm)


Aug 2017
Herbage yield (kg DM ha^{-1})
2500
2000
1500
1000
500
0
y = -0.5936x2 + 85.617x - 788.01
0
20
40
60
Plant height (cm)


Oct 2017
Herbage yield (kg DM ha^{-1})
3000
2500
2000
1500
1000
500
0
y = -0.3198x2 + 47.84x + 264.3
0
20
40
60
Plant height (cm)

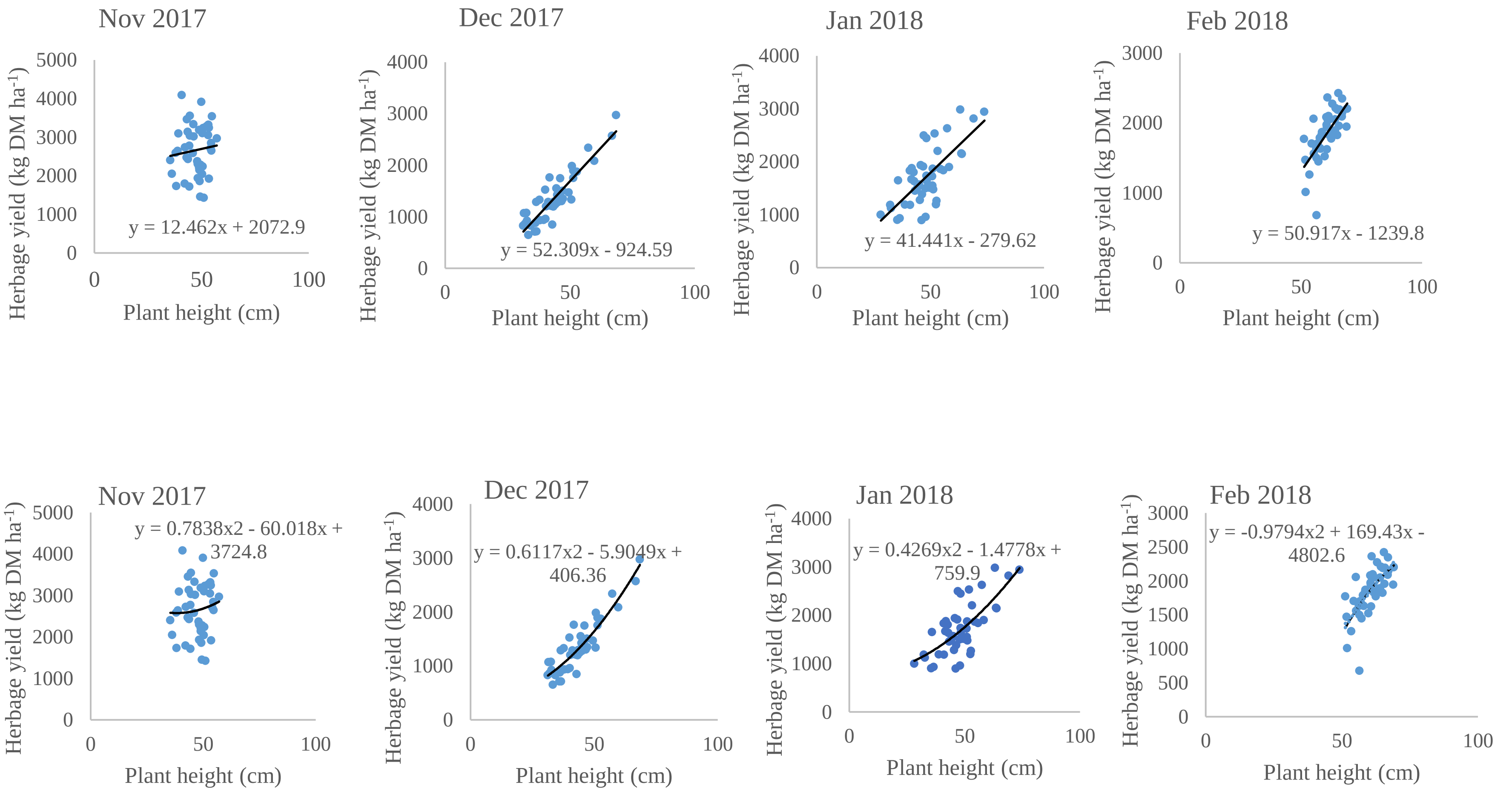
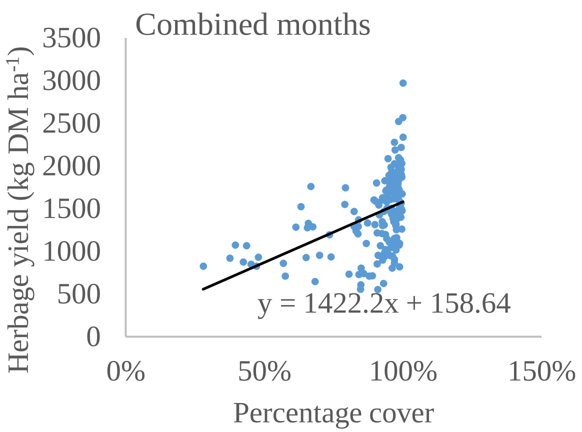
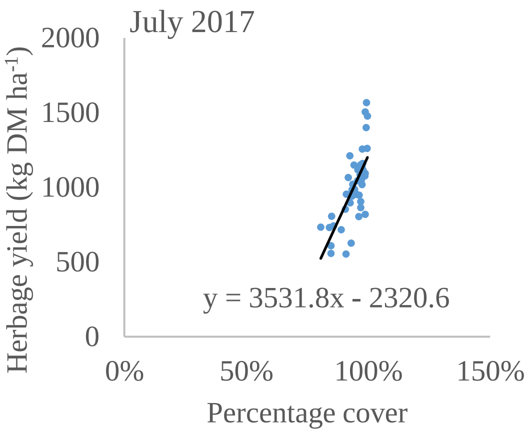
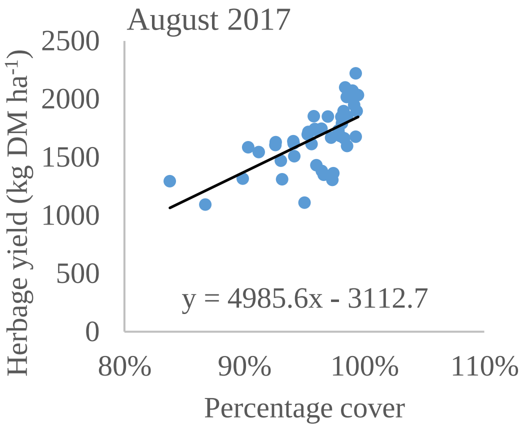
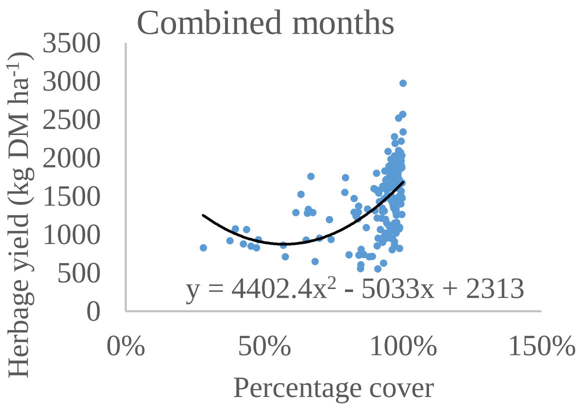


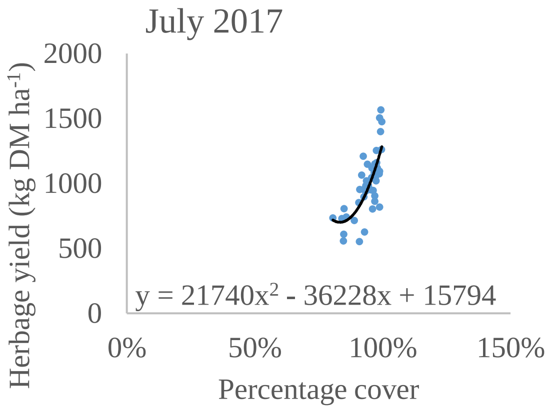
Figure 4.7: Monthly linear and quadratic meter ruler regressions for herbage yield estimation using the meter ruler. Dots scattered closer to the trendline show more accuracy of the regression in estimating lucerne yield

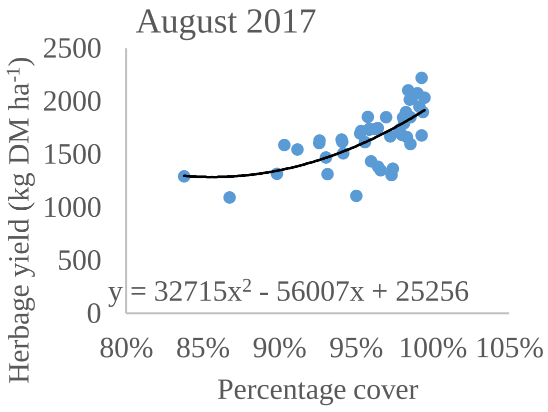

Combined months
Herbage yield (kg DM ha-1)
3500
3000
2500
2000
1500
1000
500
0
0%
50%
100%
150%
Percentage cover
y = 1422.2x + 158.64


July 2017
Herbage yield (kg DM ha-1)
2000
1500
1000
500
0
0%
50%
100%
150%
Percentage cover
y = 3531.8x - 2320.6


August 2017
Herbage yield (kg DM ha-1)
2500
2000
1500
1000
500
0
80%
90%
100%
110%
Percentage cover
y = 4985.6x - 3112.7


Combined months
Herbage yield (kg DM ha-1)
3500
3000
2500
2000
1500
1000
500
0
0%
50%
100%
150%
Percentage cover
y = 4402.4x2 - 5033x + 2313


July 2017
Herbage yield (kg DM ha-1)
2000
1500
1000
500
0
0%
50%
100%
150%
Percentage cover
y = 21740x2 - 36228x + 15794


August 2017
Herbage yield (kg DM ha-1)
2500
2000
1500
1000
500
0
80%
85%
90%
95%
100%
105%
Percentage cover
y = 32715x2 - 56007x + 25256

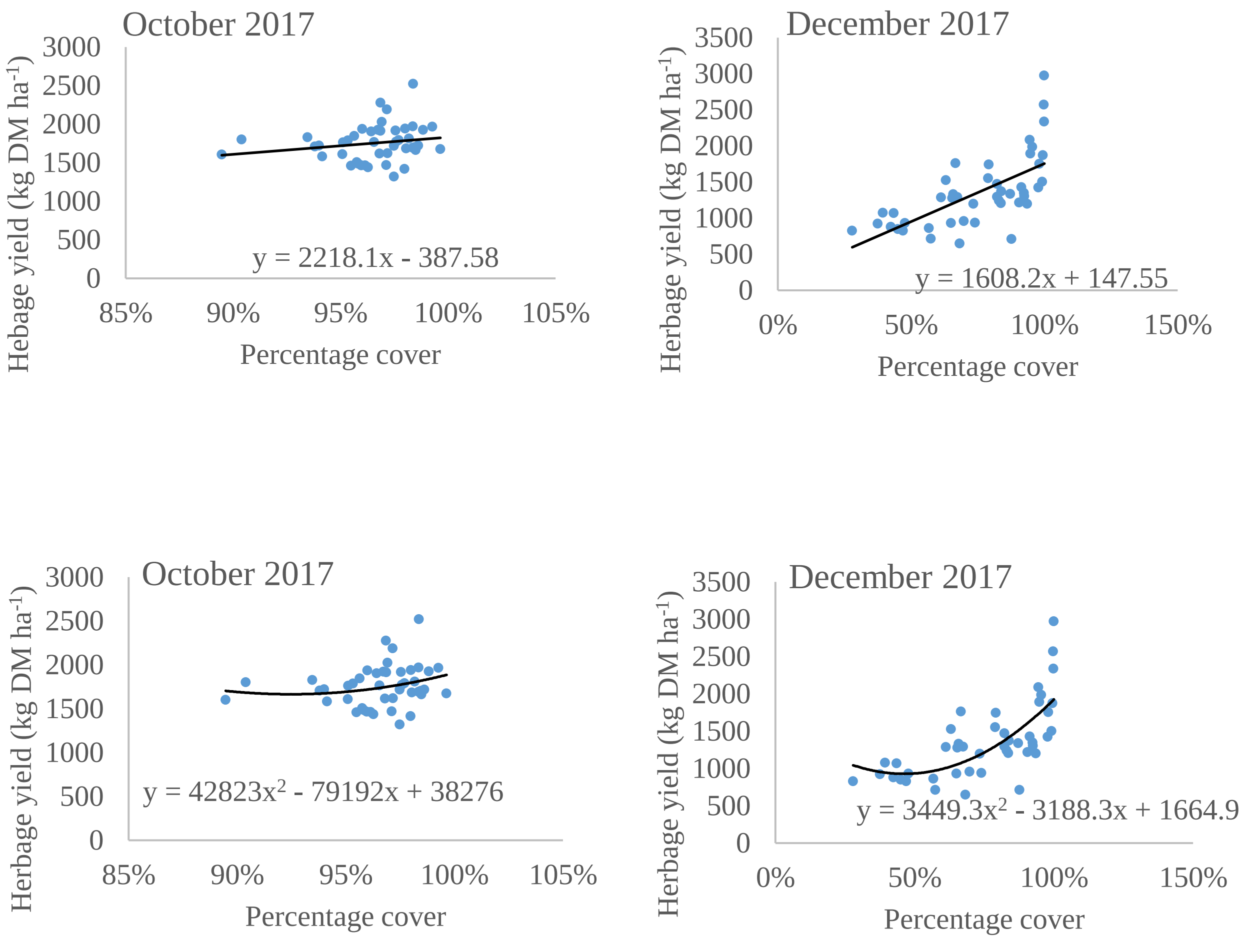


Figure 4.8: Combined and monthly linear and quadratic regressions for herbage yield estimation using the UAV. Dots scattered closer to the trendline show more accuracy of the regression in estimating lucerne yield

Chapter 5: Discussion

5.1 Herbage yield production

Monthly lucerne herbage yield for all cultivars varied from the lowest yield of 1003 kg ha^{-1} to the highest of 2661 kg ha^{-1} for 3 years from January 2015 to February 2018. Yields were low during the cooler months and highest during spring and early summer. Lattimore (2008) stated that in Australia herbage yields varied between 1000 and 4000 kg ha^{-1} per cut under irrigation. Theron and Snyman (2015) obtained highest yields of 3624 and 3401kg ha^{-1} and lowest of 902 and 864 kg ha^{-1} on soils of medium and high clay content respectively over nine growing seasons in South Africa. In the current study, herbage yield per cultivar was compiled for year three only (July 2017 – February 2018). Cultivar L70 with an intermediate dormancy produced the highest yield of 20 538 kg ha^{-1} yr^{-1}. KKS 9911 had the lowest herbage yield of 15 861 kg ha^{-1} yr^{-1}. These yields are comparable to those obtained in a study by Lawson et al. (2009) who tested lucerne in an irrigation water productivity experiment in Northern Victoria, Australia. Lucerne herbage yields ranged from 17 000 to 19 000 kg ha^{-1} yr^{-1} over a three-year trial period. Kelly at al. (2005) obtained similar yields of 17 000 to 19 000 kg ha^{-1} yr^{-1} for lucerne in a study to determine herbage production and water use. The lucerne for the current study was under full irrigation thus it was able to produce yields like those obtained by Rogers (2001) of 16 000 to 18 000 kg ha^{-1} yr^{-1} under full irrigation in Northern Victoria, Australia. Lattimore (2008) also stated potential lucerne yields ranging from 15 000 to 25 000 kg ha^{-1} yr^{-1} under irrigation. In South Africa, Theron and Snyman (2015), obtained highest lucerne yields in the second and third growing season of 22 524 and 22 640 kg ha^{-1} on medium clay content soils respectively, and on high-clay-content soils 20 442 kg ha^{-1} respectively.

The lucerne cultivars and their dormancy classes were also evaluated to determine lucerne yield potential for year one (January 2015 to December 2015). Three of the four cultivars, KKS 991, Sardi 10 and Agsalfa, that produced the lowest annual yield were from the highly winter active dormancy class. L70, a moderate winter active cultivar, had the highest annual yield amongst all cultivars. Highly winter active cultivars are expected to produce the highest yields as they are still highly productive in the colder months. However, in this study dormancy class did not affect herbage production of lucerne.

5.2 Yield estimation

5.2.1 RPM correlations

The non-destructive herbage yield estimates using the RPM was compared to the actual herbage yield from the cut-and-dry method. The overall accuracy of the RPM was good with a coefficient of determination of $r^2 = 0.69$. This was the best coefficient of determination compared to the other yield estimation instruments. Murphy et al. (1995) used the RPM to measure herbage yield and got coefficients of determination of $r^2 = 0.72$. O'Donovan et al. (2002) also tested the accuracy of the RPM together with sward stick (closely related to meter ruler) and pasture probe capacitance meter on herbage yield of swards of pastures for dairy cows. The RPM produced the highest r^2 values of 0.88 compared to those of the sward stick $r^2 = 0.87$ and 0.76 for capacitance probe (O'Donovan et al. 2002).

In the current study, monthly coefficients of determination of $r^2 = 0.53$ or higher were produced, except for November 2017 which had a coefficient of determination of $r^2 = -0.29$. The highest coefficient of determination ($r^2 = 0.90$) was for December 2017. Black and Murdoch (2013) successfully used the RPM on non-irrigated ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) to determine yield and water use under different nitrogen and irrigation regimes. Coefficients of determination also fluctuated from 0.54 to 0.94.

The reason for the low coefficient for November is not clear, but possibly could be due to an error in data capturing or experimental error. Another possible reason the RPM failed to estimate yield could possibly be the height and density of the lucerne. The lucerne produced in November 2017 was tall, thick and dense. Some herbage material got stuck between the shaft and the plate restricting free movement of the plate. This could have affected the readings taken. Tall plants can also droop over or lodge thus affecting estimations. It was found that once pastures reached a certain stage where it was drooping or falling over, the RPM's settling height did not proportionally increase to the herbage yield increase. Heady (1957) also supported this by stating that the highest point of herbage may be difficult to find if herbage material starts to droop over or trail. Likewise, Lile et al. (2001) stated that the RPM gives reliable estimates when herbage yields are lower. In the current study, the RPM was also good at estimating shorter lucerne plant stands.

5.2.2 Ceptometer correlations

The ceptometer was poor at estimating yield with a mean coefficient of determination of r^2 = 0.55. This was too low to recommend for on-farm use. However, over the monthly correlations it produced some high coefficients of determination from r^2 = 0.56 up to r^2 = 0.81. This showed the potential of the ceptometer to estimate herbage yield during the warmer and dry months of the year. Francone et al. (2014) reported a good coefficient of determination for maize (*Zea mays*) r^2 = 0.86 which is similar to some obtained in this study in individual months (August and December 2017). In this study, the ceptometer worked best under clear sunny skies

However, during the month it was cool due to season or partly cloudy skies, low coefficients of determination ranging from r^2 = 0.50 to r^2 = 0.09 were obtained. A few challenges were faced and thus could have potentially affected the accuracy of the ceptometer. After taking a reading, the probe of the ceptometer had to be wiped with a dry cloth or tissue to remove litter and moisture. Frame (1993) stated that instruments like the ceptometer and others closely related are easily affected by moisture and litter stuck onto the probe. When it became fully cloudy weather in the sky, data collection had to be stopped until the clouds passed as the ceptometer should not be operated under cloudy weather. This made the ceptometer slow to collect data.

5.2.3 Meter ruler correlations

For this study, the meter ruler was the simplest yield estimation instrument to use as it was quick and simple to operate. It also had little limitations to weather conditions. Overall the meter ruler produced a coefficient of determination of r^2 = 0.55. Low coefficients of determination can be caused by thick vegetative cover which prevents smooth penetration of the ruler to the ground. Bias by the user when collecting samples can results in poor coefficients of determination by the meter ruler (Aiken and Bransby 1992). Plant height may also be difficult to measure because of the subjectivity associated as to which plant parts are to be considered the top part for height measurement (Heady 1957). The meter ruler together with capacitance meter was used to measure herbage yield of pasture in the USA. The meter ruler was found to be inaccurate in giving estimates as it gave a low r^2 of 0.16 with the regression line less than one (Sanderson et al. 2001). In the current study, the meter ruler was found to be more efficient during months where biomass was lower such as December 2017 compared to November which was the highest.

5.2.4 Unmanned Aerial Vehicle correlations

For this study, it was noted that the UAV canopy cover estimations took the least time compared to the other yield estimation instruments It, however, produced the poorest coefficient of determination of r^2 = 0.45. When using canopy cover to estimate yield, it does not consider the weeds that can be found within the lucerne plot which may affect the accuracy of the estimates. Canopy cover could not account for plant density which also determines the amount of herbage yield. It failed to give a coefficient of determination that is applicable to practical farm use. This is contrary to a previous study by Co´rcoles et al. (2013) who successfully used the UAV to estimate canopy cover of onions. A coefficient of determination of 0.84 was obtained with a slope of 2.877 that related canopy cover with LAI. Kutnjak et al. (2015) used the UAV to estimate botanical cover on legume grass mixture of lucerne, orchard grass, and Italian ryegrass. There were positive correlations between lucerne and Italian ryegrass and aerial values obtained whilst the orchard grass had negative correlations. The use of the aerial imagery showed potential in the estimation of the botanical composition. In a study of a coniferous forest by He et al. (2013), height and percentage cover metrics were used to predict above ground herbage yield. Crown cover and mean height were found to be the best predictors of herbage yield with a coefficient of determination of r^2 = 0.74. The UAV was used for rangeland assessment, inventory, and monitoring (Laliberte and Rango 2011). Correlations between UAV images and direct estimates resulted in coefficients of determination ranging from 0.86 to 0.98. This research aimed to achieve such similar results on lucerne yield but could not.

Chapter 6: Conclusion and recommendations

6.1 Synopsis

Lucerne is an important pasture fodder crop for livestock in South Africa. It is cultivated for its hardiness, perennial habit, adaptability, ability to survive in dry conditions, together with its responsiveness to irrigation and rainfall (Lattimore 2008). In research trials, harvesting and recording yields for lucerne is done under the cut-and-dry method which is the most accurate way of collecting herbage yield data. Brummer et al. (1994) however find the cut-and-dry method to be a laborious, costly and time-consuming exercise. It is also a destructive method to evaluate yield. Cutting down on time and labour using modern technology to improve efficiency and accuracy of data collection is of utmost importance.

The aim of this study was to relate the destructive cut-and-dry method for determining lucerne yield to non-destructive estimates of yield namely; rising plate meter (RPM), ceptometer, meter ruler, and unmanned aerial vehicle (UAV). The four different instruments were used on lucerne and their estimates compared to actual yield. The trials were conducted at Elsenburg Research Farm of the Western Cape Department of Agriculture outside Stellenbosch. Yield estimation instruments were used to collect readings that were then compared to the yield determined from the cut-and-dry method.

6.1.1. Objective 1: To determine the yield potential of lucerne cultivars available commercially in South Africa.

Lucerne cultivars with different dormancy classes were tested for yield potential. Highly winter active cultivars such as Agsalfa, Sardi 10 and KKS 9911 were found to be amongst the lowest yielding cultivars. Cultivar L70, an intermediate dormancy cultivar, was found to be the highest yielding amongst all cultivars. One should expect the highly winter active cultivars to be the highest yielding cultivars as they are able to produce high yields during the winter months. However, this did not happen and therefore dormancy class did not affect herbage yield production in this study. This data was captured over a short period of time and therefore cannot be used as a guideline.

6.1.2 Objective 2: To calibrate indirect methods to estimate lucerne yield using RPM, ceptometer, and meter ruler.

The RPM had the best overall coefficient of determination compared to the other yield estimation instruments. Over the seven months of data collection, the RPM indicated it could accurately estimate yield. It operated best when the lucerne was shorter. Longer lucerne created some problems with the RPM as plant material got stuck between the plate and the shaft thereby disrupting readings. Dew also made it difficult to operate the RPM early in the morning. This gave it a limitation of it only being useful during the hot dry hours of the day, which is a limitation of using the RPM. Use of the RPM over a longer time period can be useful to calibrate it to improve its estimation accuracy. The ceptometer took the longest time to operate compared to the other three yield estimation instruments. Bending over to take readings proved to be a major challenge in operating the ceptometer which led to a lot of time being taken to operate. On days where there was dew or clouds, the ceptometer became ineffective.

The meter ruler was the easiest and simplest instrument used in this study, it was quick and simple to operate. It had the least restrictions with regards to weather conditions. It, however, did not give a high enough coefficient of determination to recommend for farm use. It was not easy to determine the highest point for measuring the height of the lucerne as each plant had many shoots, with some angling to the side.

6.1.3 Objective 3: To develop ways to us digital data collected with the unmanned aerial vehicle (UAV) to estimate lucerne yield.

The UAV has the potential to be a useful tool for estimating lucerne yield but requires a reliable service provider who will be available to accurately process the images into usable data. The year 2017 and part of 2018 were very dry due to the drought experienced in the Western Cape Province. The number of months for data collection were reduced as the study was originally scheduled to run for a total of twelve months. These conclusions are based on the current study where data was only collected for a total of seven months. However, during the months' data was collected the lucerne was able to receive enough irrigation.

6.2 General conclusion

It has shown that with a significant time period to cover all seasons of the year the RPM has the potential to accurately estimate lucerne yield. It is important to note the ceptometer is easily affected by climatic conditions as it is sensitive to rain, morning dew and cloudy skies. The

UAV has the potential to be a useful tool for estimating lucerne yield but requires a reliable service provider who will be available to accurately process the images into usable data. The year 2017 and part of 2018 were very dry due to the drought experienced in the Western Cape Province. The number of months for data collection were reduced as the study was originally scheduled to run for a total of twelve months. These conclusions are based on the current study where data was only collected for a total of seven months. However, during the months data was collected the lucerne was able to receive enough irrigation.

6.3 Limitations

This study had to be cut short due to water shortages experienced in the Western Cape Province. Data was collected for seven cuts instead of nine as initially planned, to fully cover all different season effects that might influence readings taken. The ceptometer is a difficult instrument to use when taking a high number of readings. It requires a lot of bending over and squatting which puts a lot of strain on the operators back. The UAV can only be operated by licensed individuals, and this is a problem when the operators are not available on a harvesting date. Strong winds during some harvesting dates also made it difficult to operate as the UAV could not take images that would be clear enough for use. The UAV could not be flown on all harvesting dates due to this reason. This meant less data that did not cover even half the intended data. Some of the UAV data was corrupted and could not be recovered which led to fewer data available on the already small amount of data to use. Due to unreliable service providers for UAV image processing the UAV images could not be processed in the original required method using NDVI. This played a crucial role in affecting the accuracy of the final data used to estimate lucerne yield.

6.4 Recommendations

Any further research similar to this study should be carried out over a whole year period to enable evaluation of the yield estimation instruments over a longer time period. This is to see if a longer data collection period can improve the accuracy of the yield estimation instruments. Conducting any further research also at a different site with different climatic conditions to test any potential effects of weather conditions on the accuracy of estimating yield is recommended. Further research can be done to test whether dormancy class will have a significant effect on yield estimation accuracy. It is also recommended when using the UAV to find a reliable service provider who will properly back-up and process the flight images into data that can be easily used to estimate yield. When investigating the use of the meter ruler, the centre of the crown should be used as a point of reference and not the soil surface. The ceptometer should only be operated when pasture is fully dry.

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