final report

Project code: P.PSH.0834

Prepared by: Dr Kelly Pearce, Dr Jamie Barwick, Mr Renier Bootha, Mr Phil Barrett-Lennard,
Ms Sarah Hyde, and Professor David Lamb.
Facey Group & University of New England

Date published: 22 June 2018

PUBLISHED BY
Meat and Livestock Australia Limited
PO Box 1961
NORTH SYDNEY NSW 2059

Integrating spatial technologies in a mixed farming system to increase production efficiency of crop grazing

This is an MLA Donor Company funded project.

Meat & Livestock Australia acknowledges the matching funds provided by the Australian Government to support the research and development detailed in this publication.

Abstract

This project evaluated contemporary spatial technologies to assist in crop grazing management on a mixed farming enterprise in Western Australia. There is a need for tools to better predict crop biomass to assist producers to determine when to begin crop grazing and when to remove sheep to minimise the impact on final yield. Lactating Merino ewes (n=403) and their lambs (n=425) were grazed on a barley crop for 2 weeks in June 2017. Measurement of crop biomass using quadrant cuts and Greenseeker measurement of NDVI were taken at the start and end of the trial. Low-level remote sensing (UAV) and Pastures from Space satellite imagery were also evaluated for their ability to provide near real-time biomass data. Spatial utilisation of grazed crops was determined using GNSS tracking collars and correlated with geophysical soil measurements, biomass and yield. The GNSS collars derived livestock grazing maps and harvester yield maps were also used to produce an overall *dual-purpose crop profit map* for the paddock.

A key finding from this study is that the Greenseeker can accurately predict the available biomass (kg DM/ha) when stubble is removed from the area being measured. Producers can potentially use the Greenseeker NDVI tool in conjunction with other tools to predict biomass during crop grazing and the economic potential of the paddock. The spatial grazing patterns of sheep on crop varied across the grazing period, showing higher levels of activity as available biomass declined. However, the seasonal conditions experienced early in the growing season may have supressed any relationships between grazing patterns and yield measurements. Producers should take into account the additional grazing benefits of liveweight gain and reduced supplementary feed costs from crop grazing when evaluating the gross margins of a grazed paddock. In this project, with these costs included, crop grazing resulted in a higher paddock gross margin despite a decline in crop yield. This project has identified a number of potential benefits and new areas for further research on crop grazing using spatial technologies.

Executive summary

Mixed farming in the low to medium rainfall (LR/LMR) zones in the Western Australian Wheatbelt has previously relied upon the grazing of pastures. However, changing climatic conditions are resulting in more sheep producers grazing cereal and brassica crops to provide high quality feed when pastures are still establishing in early winter to eliminate supplementary feeding. Grazing livestock on crops requires careful monitoring of the crop biomass level and development stage to ensure that the grazing period does not impinge on the reproductive development of crops, ensuring the crop can recover, regrow and produce grain. To improve the confidence of producers to adopt crop grazing, there is a need for tools to better predict crop biomass and assist producers to determine when to begin crop grazing and when to remove sheep to minimise the yield penalty.

The aim of this study was to evaluate the role of spatial technologies to measure biomass during grazing. Lactating Merino ewes (n=403) and their lambs (n=425) were grazed on a Scope barley crop for 2 weeks in June 2017. Measurement of crop biomass using quadrant cuts and Greenseeker measurement of NDVI were taken at the start and end of the grazing period. Low-level remote sensing (UAV) and Pastures from Space Satellite imagery were also evaluated for their ability to provide real time biomass data. Spatial utilisation of grazed crops was determined using GNSS tracking collars and correlated with geophysical soil measurements, biomass and yield. The GNSS derived livestock grazing maps and harvester yield maps were also used to derive an overall *dual-purpose crop profit map* for the paddock.

A key finding from this study is that the Greenseeker can accurately predict the available food on offer (FOO) (kg DM/ha) when stubble is removed from the area being measured. The predicted FOO can then be used in conjunction with other calculators that relate biomass to crop yield. In combination with exclusion cages to monitor crop growth stage, this can give producers greater confidence to graze crops and therefore increase the acceptance and uptake of this management strategy by mixed farmers.

The use of UAV's and satellites for estimating biomass change due to grazing was shown to be limited in this study given the high utilisation of available biomass by sheep. However, the UAV was a good predictor of grain yield when used later in the season and could be more appropriate for use in crop management decisions. The satellite imagery which was dependent on weather conditions resulted in poor data for critical periods of the study and therefore was not included in the majority of the analysis. However, newer satellites with a more frequent temporal resolution and lower pixel size, could improve the ability of satellite technology to predict changes in biomass and be used for crop grazing management. This report identified limitations to the use of the UAV and satellites for estimating biomass which in the short term may be overcome by the versatility of the Greenseeker.

The GNSS collars were able to demonstrate a change in spatial grazing behaviour over the 15-day trial period. However, these patterns were uncorrelated with soil quality measurements taken by geophysical testing (EM and Thorium) and with the NDVI biomass data measurements taken at paddock scale with the UAV over multiple periods. The result occurred despite a variation in biomass across the paddock. There was also no relationship between the grazing patterns and the final crop yield measured by the harvester. The paddock was very heavily grazed which may have limited the ability to detect a discernible relationship. Had there been uneven grazing due to a lower stocking rate and higher pre-grazing biomass levels in parts of the paddock, along with a better growing potential of the crop due to season, it is possible that changes in plant maturity and therefore impact on final yield may have become evident. Comparison between grazed and un-grazed treatment sites, shows an average yield penalty for grazing of 0.5t/ha. However, this difference is not consistent across all 25 sites, indicating either grazing pressure or soil properties did influence the impact grazing has on final yield.

This was the first reported study to combine the use of GNSS derived livestock grazing maps and harvester yield maps to derive an overall *dual-purpose crop profit map* for the paddock. The profit map and cost benefit analysis have shown that despite the decline in yield due to crop grazing, the economic benefits due to reduced supplementary feeding and liveweight gains may outweigh the loss of grain income. The use of GNSS collars to derive a *dual-purpose crop profit map* will be a valuable technique for the future assessment of the benefits of crop grazing. A priority should be to develop *dual-purpose crop profit map* for a prime lamb production system where crop grazing is compared to pasture/supplementary feeding systems and to also include the value of stubble grazing.

This was a pilot project with the aim of extending into a larger project in the future, further developing the application of spatial technologies in the mixed farming sector. The outcomes of this project will help determine the direction and impact of spatial technology in mixed grazing systems, with the aim of guiding future investment and partnership.

Table of contents

List of figures

List of tables

List of acronyms

AEC – Animal ethics committee

AGB – above ground biomass

BOM – Bureau of Meteorology

DM – dry matter

EM – Electromagnetic

FOO – Food on offer

GDM – green dry matter

GNSS – Global navigation satellite system

GRDC – Grains research & Development Corporation

GS – Greenseeker

Ha – hectare

IVDMD – Forage *in vitro* dry matter digestibility

LRI – Livestock residency index

LR/LMR – Low to medium rainfall

MLA – Meat & Livestock Australia

NDVI - Normalised Difference Vegetation Index

NoST – no stubble

PfS - Pastures from Space

RGB – red green blue

RSD – relative standard deviation

UAV – unmanned aerial vehicle

%CP – Percentage crude protein

1. Background

The increase in seasonal climate variation, notably the predicted decline in the winter rainfall across southern Australia (CSIRO and Bureau of Meteorology, 2015) will catalyse the need for a review of current farming systems and practices, especially in Western Australia (Kingwell et al., 2014). Farming is a high-risk business due to the immense impact that the local weather has on the production and management of different enterprises. Due to the increased risk of farming associated with the changing climate, the continued access to technologies was highlighted as an important strategy available for farmers to adapt to the changing environment. The technological advancement within broadacre farming is clearly evident with the increasing development of practices such as precision agriculture and soil testing. In contrast, the adoption of technologies within the sheep industry is slow and far behind that of broadacre enterprises (Kingwell & Pannell, 2005).

Spatial technologies have revolutionised the grains industry to date, however, there is a lack of understanding on how these and other technologies can be incorporated into mixed farming production systems to increase overall farm production. Through better understanding of the available feed on offer, improving grazed crops and pasture use efficiency, and optimised grazing pressure, there is potential to enhance animal performance and broader financial benefits for producers.

Mixed farming in the low to medium rainfall (LR/LMR) zones in the Western Australian wheatbelt has previously relied upon the grazing of pastures. However, changing climatic conditions are resulting in more sheep producers grazing cereal and brassica crops to provide high quality feed when pastures are still establishing in early winter to eliminate supplementary feeding. Modelling undertaken by the CSIRO has suggested that benefits of crop grazing to whole farm profitability are very significant, in the order of $100/ha to $200/ha (Kirkegaard, 2013).

Along with providing quality feed to the livestock during a time where there is often a feed gap, crop grazing can be a strategy used to manipulate the time of flowering (Nicholson, Frischke, & Barrett-Lennard, 2016); whether that is to avoid the frost window, and/or sowing early when the opportunity arises due to early rainfall. However, a valid concern which is evident by the number of studies on this topic is the impact grazing has on the final grain yield (Bell, Moore & Kirkegaard, 2014; Dove & Kirkegaard, 2014; Harrison, Evans, Dove, & Moore, 2011; Harrison, Evans & Moore, 2012; Nicholson et al., 2016; Seymour et al., 2015; Virgona, Gummer & Angus, 2006). Grazing livestock on crops requires careful monitoring of the crop biomass level and development stage to ensure that the grazing period does not impinge on the reproductive development of crops, ensuring the crop can recover, regrow and produce grain (Nicholson et al., 2016). Grazing crops delays flowering and can be used as a strategy post seeding to help delay the flowering time to manage frost risk when the plant is most susceptible. Grazing can also reduce canopy biomass and increase soil compaction which can reduce the severity, duration and damage from frost by modifying the soil and canopy temperature (Harrison et al., 2011).

The effect of grazing on the grain yield of crops has resulted in a range of results from yield losses of 50% or more (Kirkegaard et al., 2015; Seymour et al., 2015) to an increase in yield of more than 20% (Kelman, 2009; Miller, Dean & Ball, 2010; Virgona et al., 2006). From these studies a set of crop grazing guidelines have been compiled to ensure the impact on the yield is minimal (Nicholson et al., 2016). These guidelines include: ensuring that the plants are sufficiently anchored to withstand being pulled out by grazing (Kirkegaard et al., 2015; Seymour et al., 2015); grazing does not continue past the hollow stem stage (Zadoks stage 31) for cereals (Dove & Kirkegaard, 2014); correct varieties are selected (Bell, Harrison & Kirkegaard, 2015; Harrison et al., 2011); and sowing early if possible (Harrison et al., 2011). These guidelines are focused on crop management for yield and quality. However, very few studies have investigated the performance of the sheep enterprise when utilising a crop grazing strategy. Anecdotally, sheep are considered selective grazers and a number of research papers (e.g. Rutter, 2010) have demonstrated that sheep have a preference for pastures on particular soil types which may reflect higher nutritive value. Therefore, the spatial utilisation of crops may not be evenly distributed across the paddock and varying grazing pressure could impact the final grain yield in a crop grazing scenario.

Proactive sheep producers measure their pasture availability by measuring the biomass of the pasture which can easily be done by a number of tools (ranging in accuracy) which include pasture rulers (Harmoney, Moore, George, Brummer & Russell, 1997), rising plate meters (Miller et al., 2010) and visual assessments (Campbell & Arnold, 1973). However, these practices do not appear to be applied when crops are grazed. Few tools have been developed or adapted for accurately measuring the biomass of a crop, particularly to suit a Western Australian system. The most accurate, and industry standard approach to measure the biomass of a crop is by taking samples and oven drying them to determine the dry matter biomass. This is not only destructive but also time consuming, and is therefore not a common technique used by producers. Various sensor technologies have been used in other industries and countries which have highlighted the possibility of sensors being used for measuring the biomass of a crop, specifically for the use by a producer in the field in order to improve the performance of the sheep enterprise whilst increasing the confidence around crop grazing.

Several different sensor technologies are currently available for detecting red and near-infrared light which is used to calculate the Normalised Difference Vegetation Index (NDVI) (Andersson et al., 2017). As NDVI is strongly correlated with green biomass, these sensor technologies have the potential to be used in a crop grazing system to accurately predict crop biomass prior to and during grazing. NDVI has been used to quantify the biomass of canola (Kirkegaard et al., 2015) and pastures (Andersson et al., 2017). Sensing platforms able to provide spatial NDVI measurements include: the Greenseeker handheld active sensor (by Trimble®); an Unmanned Aerial Vehicle (UAV) equipped with a passive sensor (DJI Inspire quadcopter with MicaSense®); and available satellites via Landgate (MODIS, Sentinel, Landsat 8). The satellite data has been incorporated into the commercially available Pastures from Space (PfS) platform which has been developed to assist with the strategic management of pasture grazing (Mata, Henry, Gherardi, & Smith, 2004) but its application to crop grazing has not been defined.

This pilot project builds on the successful GRDC funded Grain and Graze program (completed in December 2016) which delivered recommendations for optimal crop grazing systems. This project aims to utilise spatial technologies to assist in the management of grazing periods and pressure by understanding changes in biomass using various spatial technologies. To our knowledge, there have been no studies conducted on the spatial behaviors of sheep on grazed crops during the growing season using GNSS animal tracking and correlating these behaviors to changes in NDVI, soil history, animal performance and final crop yield. This project will develop a methodology to assess the spatial variation in crop grazing and understand potential relationships to soil quality, biomass/NDVI and final grain yield.

2. Project objectives

Priority aims:

- To demonstrate that integrating spatial crop, soil and livestock technologies can better inform management decisions when grazing crops and lift crop grazing efficiency.
- To better understand the grazing patterns of livestock when grazing crops and link to crop yield maps at harvest.
- To generate livestock yield maps at a sub-paddock scale developed by integrating plant-monitoring technologies quantified to GPS derived animal grazing patterns.
- Increase capacity and understanding of precision agriculture for livestock production in WA.

Desirable aims:

- To understand of the relationships and correlations between the spatial and temporal variability in soil nutrients and biomass with grazing patterns and preferences of grazed crops and stubble.
- To understand the cost benefits of crop grazing under the experimental conditions of this study.

3. Methodology

3.1 Experimental site

This project was conducted at Manton Farm at Yealering in Western Australia, 220km, South West of Perth (Figure 1). The paddock was 68ha consisting of sandy loam soils. There were two watering points: a dam located on the eastern border and trough on the northern boundary. There was no shelter available in the paddock. The project sites average annual temperature range from 32.6°C in January to 4.8°C in August with a yearly annual rainfall of 373mm (BOM, 2018). The 2017 rainfall pattern varied considerably from the long-term average in the Yealering area, as shown in Figure 2. All trial details are listed in Table 1.

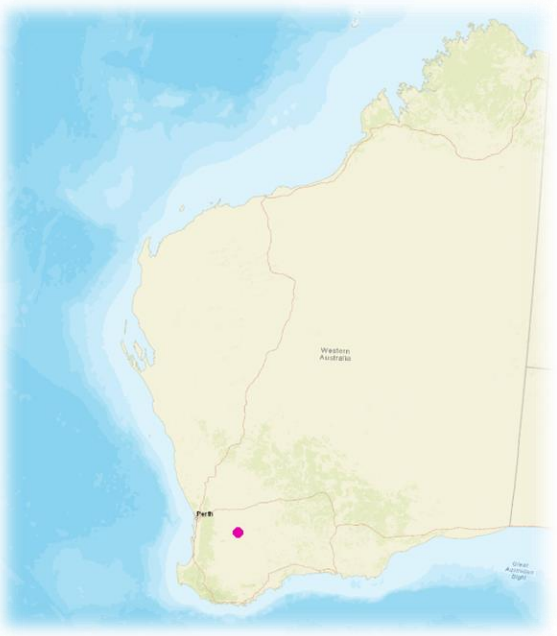


Figure 1. Location of project site at Yealering in Western Australia.

Table 1. Summary of trial details including management practices conducted on the trial site.

Property:	Manton Farm - Alan Manton and Kelly Pearce, Yealering WA
Paddock Size:	68ha with exclusion zones within paddock
Soil type:	Sandy Loam
Crop Variety:	Scope Barley
Sowing Date:	8th May 2017
Seeding Rate:	75kg/ha
Fertiliser:	10.4.2017 – SOA @130kg/ha 8.5.2017 – 45kg MAP & 20kg MOP 15.7.2017 – 30L UAN 24.8.2017 – 30L UAN

Herbicides/Fungicides/Insecticides:	8.5.2017 – 0.5L Paraquat, 2L Trifluralin, 0.3kg Diuron 25.7.2017 – 0.04kg Lontrel, 500mL MCPA LVE 570, 900ml Jaguar 17.8.2017 – 3L Prosulfucarb, 230mL Propiconazole 550 24.8.2017 – 50mL Alpha cypermethrin, 115mL Propiconazole
Grazing Date enter:	23.06.2017
Grazing Date remove:	9.07.2017 (16 days grazing)
Mob Size	403 Ewes (Merino) and 425 Lambs (White Suffolk X Merino) born April 2017

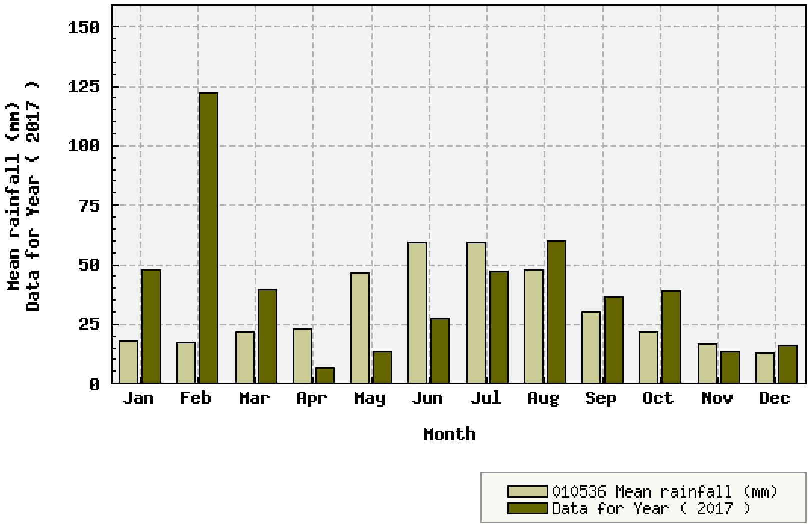


Figure 2. The long term average and 2017 monthly rainfall pattern. Note the lower than average rainfall received early in the growing season for April, May and June (BOM, 2018).

3.2 Experimental design

Prior to the commencement of the experiment, a geophysical survey for EM38, gamma radiometrics, and elevation was supplied through Precision Agronomics. This data along with historical yield data and satellite NDVI data was used for selecting soil coring sites which were analysed to ground-truth the geophysical data. Twenty five sites across the paddock were selected (Figure 3), representing the in-paddock variation revealed within the ground-truthed geophysical data. Each of these sites consisted of a square caged area, constructed from four 2.8m sheep panels which acted as an exclusion zone during sheep grazing. This area represented the “ungrazed treatment” (Figure 4). Adjacent to each of these exclusion zones was a plot of the same dimensions (2.8m x 2.8m) available for grazing to represent the “grazed treatment”. The arrangement of the grazed and ungrazed treatment sites is summarised in Figure 5.

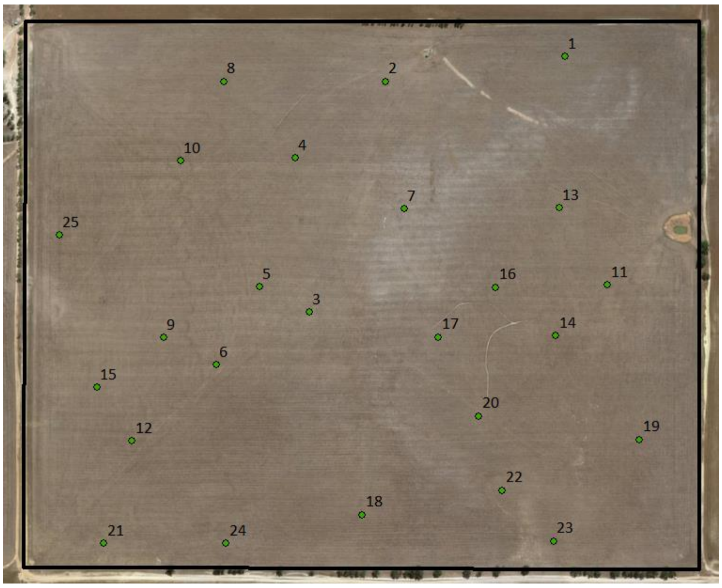


Figure 3. The 25 site locations selected based on the ground-truthed geophysical data to represent the in-paddock spatial variation.

Figure 4. Example of an exclusion cage for the ungrazed treatment.

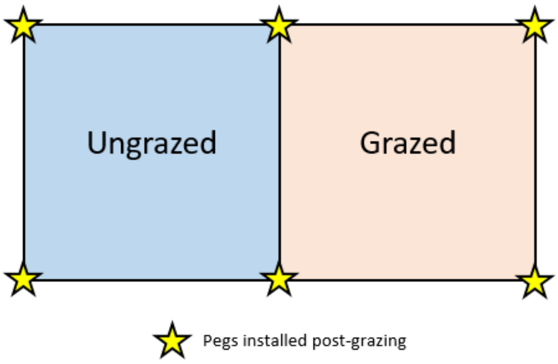


Figure 5. A diagrammatic illustration of the design of the plots with the caged area and adjacent grazed sampling area.

3.3 Biomass sampling

Three biomass measurement events were conducted throughout the trial. Additionally, Zadoks (Zadocks, Chang, & Konzak, 1974) growth stages of the crop at each site, within each treatment was assessed periodically following the end of the grazing period throughout the remainder of the growing season (eight times between 15/08/2017 – 5/10/2017).

3.3.1 Pre - grazing

Pre-grazing crop measurements were taken at each of the 25 sites on the 21st of June 2017. The measurements included: plants/m^2, plant height, Greenseeker NDVI, stubble biomass and crop biomass weight. A quadrant (70cm x 30cm) was randomly placed within the marked-off area adjacent to the cage of the plot (refer to Figure 5). The crop height (cm) was measured with a ruler from ground level at the centre of the quadrant. The stubble within the quadrant for each plot was removed and placed into a large paper bag for further processing. Following the removal of the stubble, four sequential plant biomass samples were taken from the one row within the quadrant (Figure 6) by cutting a small proportion of the biomass with shears, then placing the cuttings into separate small paper bags for further analysis. The fourth and last cutting was cut to ground level.

Figure 6. The quadrant within the sampling area placed lengthwise along the row with the crop and stubble still present.

In addition to the biomass samples taken from within the quadrant, further samples were taken at ten of the plots from within the sample area (grazed treatment) to be used for the forage crude protein (%CP) and forage *in vitro* dry matter digestibility (IVDMD) analyses. These samples were randomly taken from within this open area as a minimum of 300g of fresh biomass was required to conduct the forage laboratory analyses according to the AFIA -Laboratory Methods Manual (Li et al., 2009). The samples were placed in clearly marked plastic, sealable sandwich bags and immediately moved into a freezer until the laboratory analyses was commenced.

3.3.2 Post-grazing

Post-grazing measurements were taken on the 10th of July 2017 (1 day post grazing). This sampling event was identical to the pre grazing measurements, with the addition of sampling the exclusion zones (ungrazed treatment). Due to little biomass remaining outside the exclusion zones (grazed treatment), only one biomass cut (no sequential cuts) was taken which removed all the biomass within the quadrant.

3.3.3 Harvest

Harvesting occurred on the 13th of November 2017. Battery-powered cutters were used to harvest the barley by cutting four, 1m rows at ground level (Figure 7) . Both ungrazed and grazed treatments were harvested at each site (50 harvest cuts in total).

The paddock was harvested on the 20th of November 2017 by a New Holland harvester with an in-built yield monitor.

Figure 7. A harvested section of the barley crop at one of the plots.

3.4 Laboratory analysis

The stubble and biomass samples taken from each plot at pre-grazing and post-grazing were weighed to record biomass wet weights. To dry the samples, they were placed in an oven for 24 hours at 80°C. Once dried the bags with the samples were weighed and dry weights were recorded. These weights were converted to levels of feed-on-offer (FOO) in kg DM/ha.

Complete harvest cuts were weighed to establish the above ground biomass (AGB) for each of the samples prior to threshing to extract the grain. Threshing was conducted at the Department of Agriculture and Food facilities in Northam using their on-site Kimseed multi-thresher CW09 following the manufacturers guidelines.

3.4.1 Forage *in vitro* dry matter digestibility and crude protein

Preparing the forage samples for analysis required the sample from each plot to be placed on separate aluminium trays and oven dried for 48 hours at 65°C. Once the samples had been dried, each sample was milled through a 1mm screen using a FOSS Cyclotec Sample Mill. The milled samples were placed in sealable plastic bags for storage until further analysis.

The *in vitro* dry matter digestibility of the forage samples was determined by the reference method (Method – 1.7R: Determination of Digestibility using Pepsin – Cellulase Method) in the AFIA - Laboratory Methods Manual (Li et al., 2009). No α-amylase solution was added on day two of the analysis due to the type of sample analysed. Further, the sample dry matter was determined by placing approximately 1.5g of grounded sample into a crucible and placing it in a fan-forced oven for 24 hours at 105°C following the procedure set out in the AFIA – Laboratory Methods Manual Method 1.3R: Determination of Dry Matter (Li et al., 2009).

The crude protein percentages for the forage samples were determined following the reference method (Method – 1.4R: Determination of Crude Protein by the Kjeldahl method) of the AFIA – Laboratory Methods Manual (Li et al., 2009). Kjeltabs 1527-0003 were used as the catalyst for all samples, with a sample weight of 0.3g. The heater block used was a FOSS Tecator™ Digestor and the distillation was carried out on the auto distillation unit FOSS Kjeltec™ 8200. The titration was carried out using hydrochloric acid (0.1N) instead of sulphuric acid as per the reference method. The %Nitrogen of the samples were calculated according to the equation given in the AFIA – Laboratory Methods Manual with the crude protein percentage (%CP) calculated by multiplying the %N by 6.25 (Li et al., 2009).

3.4.2 Grain yield and crude protein

The grain samples for each plot and treatment were weighed to establish the yield from the sampled area (g/m^2), which was then converted to kg/ha. The 100-grain weights of each sample were measured by randomly selecting grains from each sample bag and manually counting out 100 grains and weighing these, this was repeated three times per sample. Once the three 100 grain sample weights were recorded the three samples were combined and milled through a 1mm screen with the Cyclotec sample mill. The ground samples were placed into small sealable plastic bags until the crude protein analyses. The grain crude protein (%CP) was determined by the same method as the forage crude protein, however, 0.5g of ground grain was used for the grain %CP analyses.

3.5 NDVI measurements

Three Normalised Difference Vegetation Index (NDVI) measurement platforms were used: Greenseeker, unmanned aerial vehicle (UAV) and satellite.

3.5.1 Greenseeker

The Greenseeker (GS) readings were taken from a height of 1m (Miller et al., 2010), to ensure the GS footprint was equivalent to that of the quadrant at 70cm x 30cm (Campbell & Arnold 1973). At the pre and post-grazing sampling events, an initial NDVI reading was taken with the stubble present, then a subsequent reading was taken after the removal of the stubble with four sequential readings after a portion of the biomass was removed (as described in Section 3.3.1). During the post grazing measurements, the grazed treatment did not have enough biomass for the sequential cuts, therefore only three readings were taken (GS with stubble, GS without stubble and GS post biomass cut). No NDVI measurements were conducted at harvest.

Figure 8. The Greenseeker attached to a PVC pipe being used to take a NDVI reading at a height of 1m.

3.5.2 Unmanned aerial vehicle (UAV)

The unmanned aerial vehicle (UAV) flights were coordinated by Precision Agronomics along with the initial data processing to produce the NDVI orthomosaics. The UAV used was a DJI Inspire quadcopter, with an RGB camera for the initial flight (UAV F1) at crop emergence. All the subsequent UAV flights were conducted with the UAV fitted with a Micasense® camera that takes images in the visible (RGB) and infrared (near infrared and red edge) spectral bands. The UAV flights were conducted as close to the overpasses scheduled for Landsat 8 and Sentinel (2 and 3) satellites. Flights occurred between 10am and 2pm at 400’ elevation, with 90% image overlap. UAV data was obtained on 06/07/2017 (UAV F2), 17/07/2017 (UAV F3), 07/08/2017 (UAV F4) and 23/08/2017 (UAV F5). The resulting images were processed in Pix4D® and ArcGIS® to produce the NDVI orthomosaics. A John Deere Greenstar® differential real-time kinematic GNSS was used to survey the reference points for accurate georeferencing of the orthomosaic images.

3.5.3 Satellites

The satellite data for this project was managed, processed, and supplied by Landgate Imagery Products and Services. Satellite NDVI data was obtained from three different satellite platforms: Landsat 8, Sentinel (2 and 3) and MODIS. Due to cloud cover, data were not always available from all the satellites. Landgate supplied the available satellite data along with the UAV data that they had processed to ensure the different data sets were all georeferenced precisely to match the locations of the plots. The Sentinel data from 13/06/2017 were the only satellite data available to be used with the pre-grazing measurements. Similarly, Landsat 8 was the only satellite with usable data for the post grazing analyses. No MODIS satellite data were used in any of the analyses as the data obtained are at paddock scale and therefore no variability is shown at the site or sub-paddock level.

Because the Landsat pixels are 30m x 30m, they are too large to detect variation within and outside the grazing exclusion cages but the data was tabulated in the same manner for consistency. The shortage of concurrent imagery data precludes attempting to establish a formal correlation between datasets.

Comparisons between the grazed and ungrazed treatments were performed. Within each grazing exclusion cage 20 pixels were sampled at random and the average NDVI value calculated for inside the cage. Grazed samples outside the cages used a polygon the same size as the cage placed to the north, south, east and west of the cage (Figure 9). These sample areas were moved away from sheep traffic wear paths around cages to ensure a representative area was sampled outside but near the cage.

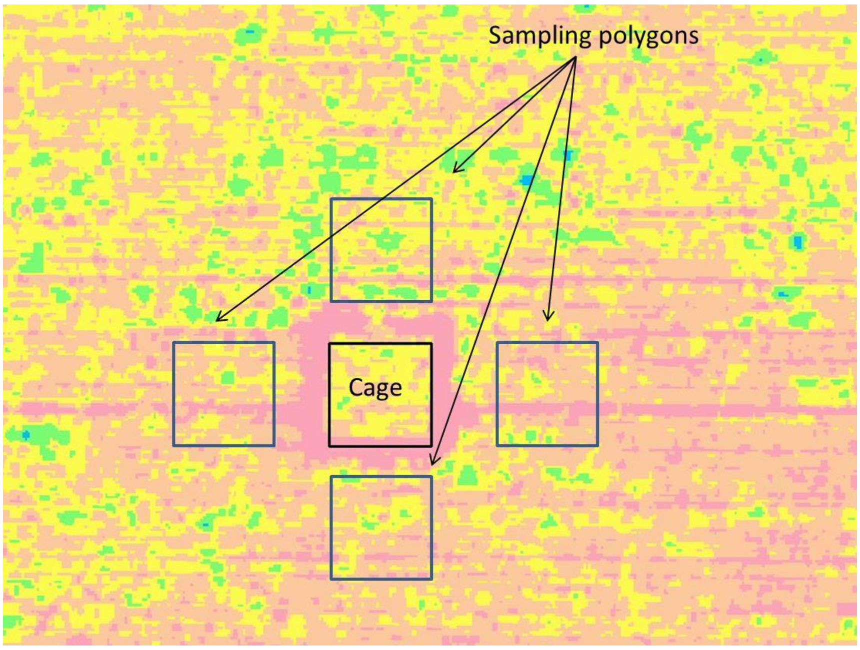


Figure 9. Imagery sampling polygons for grazed and ungrazed treatments.

3.6 Livestock & grazing management

The procedures that involved animals were approved by the University of New England Animal Ethics Committee (Authority No. AEC17-006), with approval based on the *UNE Code of Practice for Experimental Animals*, the *Australian Code of Practice for the Care and Use of Animals for Scientific Purposes 2004*, and the *NSW Animal Research Act 1985* and *NSW Animal Research Regulation 2005*.

Grazing of the paddock commenced on 23/06/2017 with a mob of 403 Merino ewes and 425 of their crossbred lamb progeny (born April 2017). The mob was previously on a pasture paddock with access to EasyOne pellets (Milne Feeds) and ad lib hay given twice a week, with the average ewe weight of 57.4kg (n = 47) at condition score 2.2, and the average lamb weight of 21.1kg (n = 40) prior to grazing the crop. The sheep had access to the whole barley paddock (68ha) except the 25 cages (ungrazed treatment) at a stocking rate of approximately 18 DSE/ha. The sheep grazed the paddock until removal on 9/07/2017 which equated to 16 days of grazing. The liveweights and condition scores of 47 ewes and liveweights of 40 lambs were taken at pre-grazing and post. From this group, a subset of 20 ewes had UNEtracker II GPS collars deployed (Figure 10) (Trotter et al. 2010). The GPS collars recorded 4, 10 second burst logs at 10 minute intervals. This dataset had HDOP values greater than 3 removed and speeds greater than 3m/s removed (as these were viewed as being inaccurate records). Speeds greater than 0.05m/s were categorised as grazing and speeds less than or equal to 0.05 categorised as resting, in accordance with the methodology of Putfarken, Dengler, Lehman & Hardtle (2008). Collars were removed prior to the final weighing.

Figure 10. Deploying a GNSS tracking collar on a ewe.

3.7 Data processing

3.7.1 GNSS Tracking collars

A series of processes using ArcMap 10.2 and R studio were carried out to clean the data and remove all erroneous data points. All positional fixes that did not fall within the trial period parameters were removed. The 10 second bursts were used to calculate velocity (metres/second) with unreasonable velocities >3.0m/s removed.

3.7.2 Livestock Residency Index (LRI)

Sheep tracking data was processed into a 10x10m livestock residency index (LRI) grid. An LRI is the number of GPS fixes recorded in a particular grid cell location as a proportion of the total GPS fixes recorded across the paddock (Equation 1). The analysis was broken down into 3 time periods:

- Days 1-3 (24/6/18 to 26/6/18)
- Days 7-9 (30/6/18 to 2/7/18)
- Days 13-15 (6/7/18 to 8/7/18)

The LRI for any given grid cell (x) was calculated using the following equation:

$$LRIx = \frac{\sum x \; Raw \; point \; count}{\sum n \sum x \; Raw \; point \; count} \times 100 \qquad \textit{(Equation 1)}$$

Where *n* is the total number of cells.

The LRI creates a ‘heat map’ highlighting areas within the paddock that have a high utilisation by animals. The 20 collared animals acted as a representative subset of the entire flock.

3.7.3 Diurnal Activity

A 24 hour diurnal activity pattern was calculated for each time period, using the average speed of all collared animals across the 3 day period. The 10 second bursts were used to calculate velocity (metres/second) for each GPS tracking collar. This was calculated to show the variation in activity over a 24 hour period and how this changed across the crop grazing window.

3.7.4 Drone Biomass

NDVI values for drone flights 2, 3, 4 and 5 were calculated using *Equation 2*. Using the calibration curve derived from the pooled grazed and ungrazed biomass/NDVI measurements, the paddock biomass was calculated using *Equation 3*. These NDVI values were converted into an average value for each grid cell and correlated with grazing, EM and yield data layers.

$$NDVI = \frac{NIR-Red}{NIR+Red} \qquad \textit{(Equation 2)}$$

$$Biomass = 1294(NDVI) - 104 \qquad \textit{(Equation 3)}$$

3.7.5 Soil survey – EM38 and thorium

Historic soil EM38 and radiometric (thorium) paddock survey data was interpolated from point data onto a 10x10m raster grid using an ordinary kriging method and an exponential semivariogram model in ArcGIS. This allowed visual comparison and regression with other data layers (yield, LRI, NDVI)

3.7.6 Grain Yield data from harvester

Grain yield data was provided from the inbuilt yield monitor in the harvester. Data were cleaned to remove end of row and inaccurate yield points and krigged onto a common 10x10m grid file using an ordinary kriging method and an exponential semivariogram model in ArcGIS.

3.8 Statistical analysis

3.8.1 Regression analysis - sites

The statistical analyses were conducted using Microsoft Excel 365 ProPlus and GenStat Undergraduate Release 16.1. The data from each measurement was placed into a data set which resulted in four separate data sets: forage, pre-grazing, post grazing and harvest. The data from each data set was visualised on scatter plots to investigate the distribution prior to performing correlation and general regression analyses on each data set. Additionally, two-tailed t-tests were used to test for significant differences between the means of the parameters from the separate data sets. The response variates in the general regression analyses, were crude protein (%CP) and *in vitro* dry matter digestibility (IVDMD) within the forage data set; and FOO (kg DM/ha) within the pre-grazing and post grazing data sets. The relevant NDVI values (from the different technologies) and height (cm) were the key variables for each regression analysis, however pre-grazing FOO (kg DM/ha) was included in the forage data set regression analysis as an additional variable. Similarly, stubble biomass (kg DM/ha) was included in the pre-grazing and post grazing regression analyses. The regression analysis for the harvest data set included grain crude protein (%CP) and grain yield (t/ha) as the response variates, with above ground biomass (AGB) taken at harvest, the post grazing FOO (kg DM/ha), the post grazing NDVI values, the post grazing height (cm), and the UAV flight 5 NDVI values as the explanatory variates. Each general regression analysis initially included all the parameters, with the non-significant terms ($P > 0.05$) sequentially removed from the models, however the raw data was checked in the event that the result could have been driven by outliers. Following the analysis of each data set, a pooled data set was created by combining the pre-grazing and post grazing data sets, with an additional general regression analysis performed on this pooled data set.

The laboratory analyses to determine the forage IVDMD, forage %CP and grain %CP were performed in replicates for each sample, thus two or more sub-samples analysed separately. This resulted in an unbalanced data set due to only having one entry for the other parameters per sample (plot). Following an initial investigation, it was concluded that the mean values of the samples from laboratory results were to be used in the regression analyses, therefore having a balanced data set.

During the initial post grazing data set regression analysis, several warning messages were given which required an assessment of the raw data. Following the assessment, several outliers were removed from the data set with the details given in Table 2. It was concluded that these outliers were most likely due to human error during the measuring in the paddock as no discrepancies existed between the hand-written record sheet and the electronic data sheets.

Table 2. Outliers that were removed from data sets and the respective reasons.

Data set	Plot	Treatment	Reason
Post-grazing	3	Grazed	Very high NDVI values compared to the rest of the plots in comparison to biomass present
Post-grazing	6	Grazed	Very high wet biomass value, similar value to ungrazed treatment, however dried weight fine therefore resulting in a very low DM of 5%
Post-grazing	2	Ungrazed	Discrepancies with biomass weight as this plot was not sampled in sequential cuts therefore different bag used. Possibly incorrect bag used thus incorrect weight deducted
Post-grazing	8	Ungrazed	Discrepancies with biomass weight as this plot was not sampled in sequential cuts therefore different bag used. Possibly incorrect bag used thus incorrect weight deducted

3.8.2 Regression analysis – whole paddock level

All layers of paddock scale data were sampled onto the same 10x10m grid file to allow regression between multiple layers. Regression and multiple regression analysis was performed in Microsoft Excel on both the 25 site locations and across the entire paddock using the 10x10m grid file. The regressions performed are shown in Table 6.

3.9 Cost benefit analysis of crop grazing

The actual physical and financial performance of the grazed paddock was compared to the predicted performance of the paddock if it had been left ungrazed. A “Potential” yield map for a hypothetical ungrazed crop was developed based on the average yield difference between grazed and ungrazed locations (inside and outside exclusion cages). Livestock figures were excluded from this analysis.

The following assumptions and costings were made:

- At harvest, all the grain deliveries from the experimental paddock went Malt barley, however, assessment of the individual ungrazed paddock cages indicates that the paddock could have gone feed barley and therefore yielding lower value grain if it was ungrazed. To come to this conclusion, the grain quality determined by both the grain handler CBH and the laboratory of ungrazed cages were assessed and the majority of the cages were of feed barley grade.
- The average difference in yields between the grazed and ungrazed cages was used to determine the difference in yield between the scenarios. The yield difference was 0.54t/ha, hence every paddock yield value was increased by 0.54t/ha, even though some grazed sites had a higher yield than their corresponding ungrazed site.

- The weight gain of lambs over the 16 day trial period was distributed across the grazing LRI map (i.e. each grid cell LRI value x total weight gain).
- Grain production costs were identical for both grazed and ungrazed scenarios and distributed evenly across the paddock as no variable rate technology was utilised.
- Expenses = $202.60/ha. This is crop-only costs. Sheep associated costs were not included.
- Income from grain (malt barley) = $237.09/tonne
- Income from grain (feed barley) = $217.17/tonne
- Income from lambs = $5.50/kg (carcass weight calculated as 45% of liveweight)
- Income from ewes = $3.30/kg
- Total lamb weight = 1828kg (based on an average gain of 4.3kg for weighed lambs)
- Total ewe weight = 927kg (based on an average gain of 2.5kg for weighed ewes)

4. Results

4.1 Geophysical soil information

4.1.1 Elevation

The elevation increases in a diagonal pattern across the paddock ranging from 274m in the North Eastern corner to 299m in the south western corner. The highest point in the paddock is in the south eastern corner at an elevation of 303m.

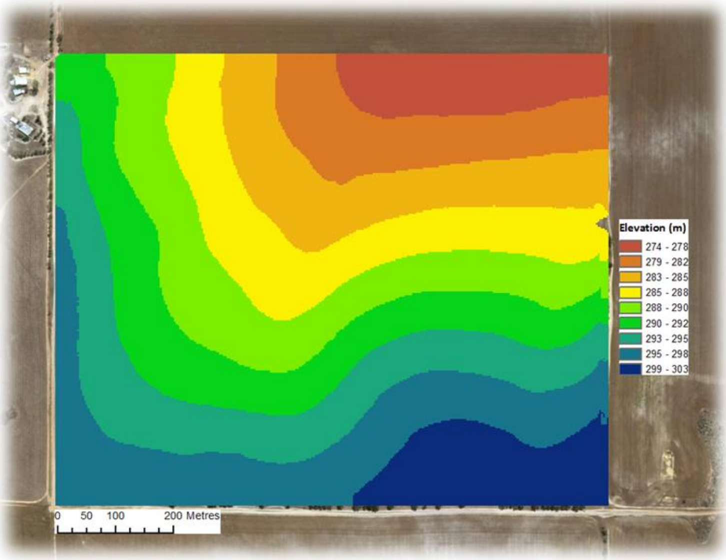


Figure 11. Elevation map of the trail paddock conducted by Precision Agronomics.

4.1.2 Electromagnetic induction – EM38

The EM38 values vary across the trial paddock however there is no clear pattern and there appears to be little relationship with elevation.

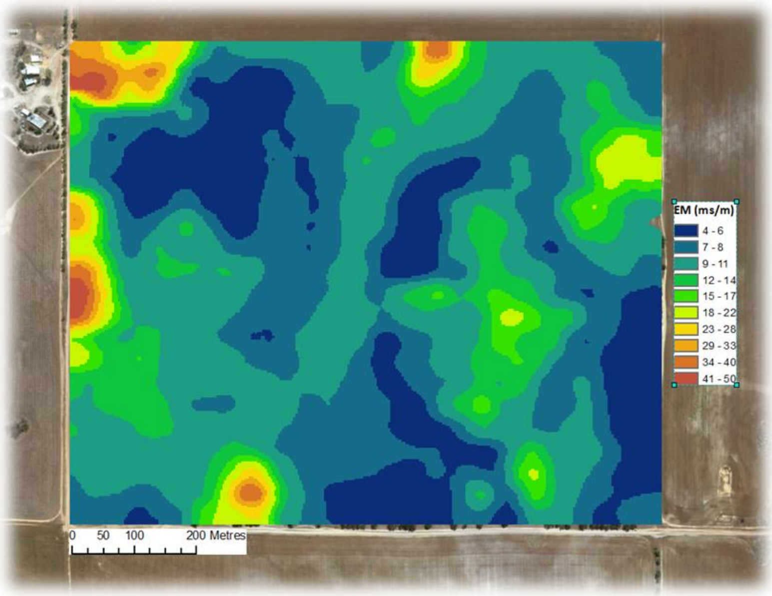


Figure 12. EM38 map of the trial paddock conducted by Precision Agronomics.

4.1.3 Radiometrics – thorium

The radiometric values have two dominant areas of high readings on the western border and south-west of the dam on the eastern border.

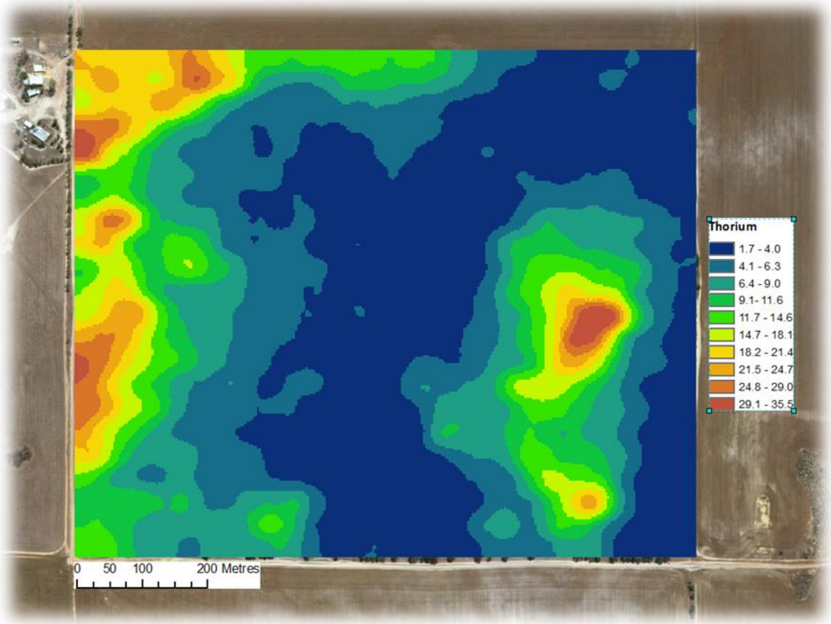


Figure 13. Radiometric thorium map of the trial paddock conducted by Precision Agronomics.

4.2 Crop and animal performance

4.2.1 Change in biomass due to crop grazing

The mean feed-on-offer (FOO kg DM/ha) prior to the sheep entering the paddock to begin grazing (pre-grazing) was 87.87kg DM/ha with some parts of the paddock as high as 150kg DM/ha (Table 3). The ungrazed plots resulted in a significantly higher estimated mean FOO of 394.5kg DM/ha by the time of post-grazing measurement (one day after sheep were removed) compared to the grazed treatment that resulted in a mean FOO of 96.52kg DM/ha remaining after the sheep were removed from the paddock. There were significant differences between the pre-grazing, ungrazed, and grazed dry matter (%DM) content with the post-grazing grazed treatment at 41%DM; 19%DM for the post-grazing ungrazed treatment, and 27%DM at pre-grazing (Table 3). The crude protein percentage (%CP) and *in vitro* dry matter digestibility (IVDMD) for the ten samples of forage taken at pre-grazing were 32% and 76% respectively.

Table 3. The mean ± SE and range for the crop parameters measured and quality parameters obtained from laboratory analysis, at pre-grazing and post. Different superscript letters in the same row indicate significant differences (P<0.05). *n = 10

	Pre-grazing		Post-grazing			
	(n=25)		Ungrazed (n=23)		Grazed (n=23)	
	Mean ± SE	Range	Mean ± SE	Range	Mean ± SE	Range
FOO kg DM/ha	87.87 ± 5.86^{a}	37.7 - 150.2	394.5 ± 30.68^{b}	177.6 - 670.9	96.52 ± 10.99^{a}	33.7 - 257.5
Stubble kg DM/ha	164.5 ± 17.45^{ab}	6.6 - 344.2	223.4 ± 26.45^{a}	67.1 - 602.7	140.2 ± 18.98^{b}	48.2 - 464.9
Height	13.92 ± 0.71^{a}	8.0 - 22.0	25.87 ± 0.73^{b}	21.0 - 35.0	5.00 ± 0.24^{c}	3.0 - 7.0
% DM	25.56 ± 1.1^{a}	17.8 - 37.3	18.8 ± 0.44^{b}	13.8 - 21.8	41.17 ± 2.81^{c}	23.3 - 78.31
% CP	31.76 ± 0.54*	28.9 - 34.2				
IVDMD	76.3 ± 1.13*	70.9 - 81.2				

4.2.2 Grain yield and protein

The mean grain yield for the ungrazed plots was 3.8t/ha with several plots yielding above 4.5t/ha. The grazed plots had a significantly (P = 0.03) lower mean yield of 3.3t/ha (Table 4). The yields ranged from 1.7t/ha to 5.2t/h for both the grazed and ungrazed plots with Figure 14 showing the variation across the paddock. Additionally, the above ground biomass (AGB) for the ungrazed plots were higher than that of the grazed plots with 7.8t/ha and 7.2t/ha respectively (Table 4). The grazed plots resulted in a mean %CP of 8.8% whilst the ungrazed plots resulted in a significantly lower %CP of 7.5% (P<.001).

Table 4. The mean ± SE and range for grain protein (%CP), calculated yield (t/ha), above ground biomass (AGB) and 100 grain weight (g) for ungrazed and grazed plots at harvest. Different superscript letters in the same row indicate significant differences (P<0.05), ns = no significant difference (P>0.05).

	Ungrazed (n=25)		Grazed (n=25)	
	Mean ± SE	Range	Mean ± SE	Range
% CP	7.47 ± 0.13^{a}	6.0 - 8.7	8.76 ± 0.14^{b}	7.4 - 10.5
Yield (t/ha)	3.82 ± 0.16^{a}	1.7 - 5.2	3.28 ± 0.17^{b}	1.7 - 5.1
AGB (t/ha)	7.78 ± 0.32^{ns}	3.6 - 10.5	7.17 ± 0.37^{ns}	4.1 - 11.1
100 grain weight (g)	4.71 ± 0.03^{ns}	4.2 - 5.0	4.73 ± 0.03^{ns}	4.4 - 5.0

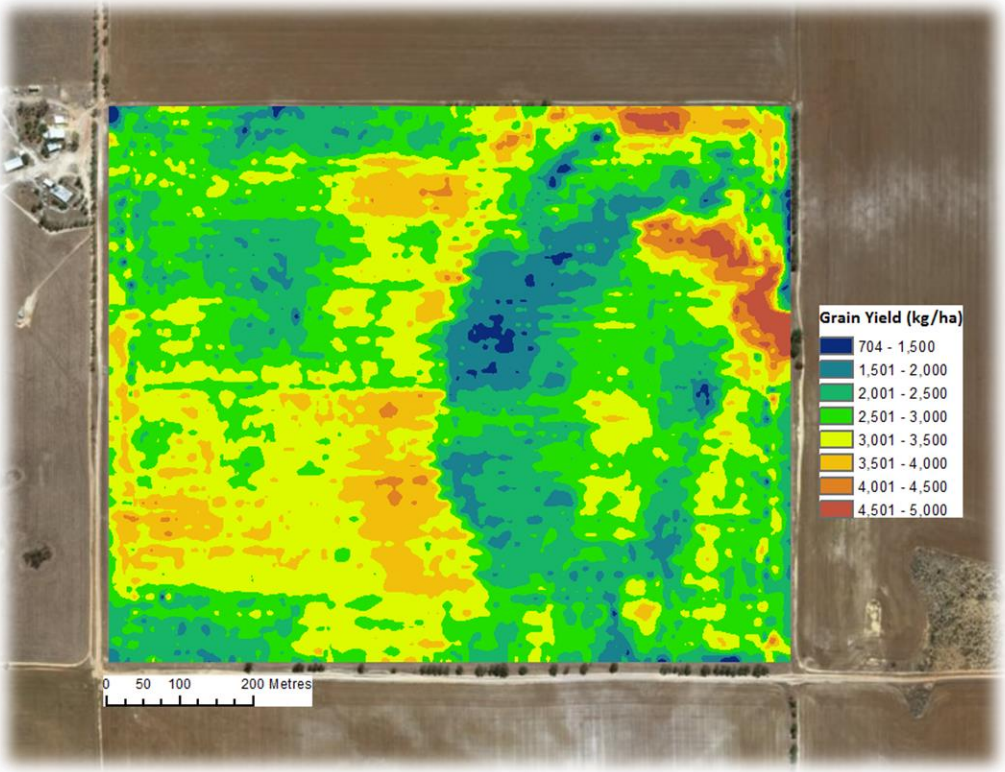


Figure 14. Krigged 2017 barley grain yield (kg/ha) showing the spatial variability in final grain yield across the paddock.

4.2.3 Sheep and lamb weights and condition score

Both the ewes and lambs all gained weight and condition score over the two-week grazing period. The ewes gained on average 150g/head/day and half a condition score whilst the lambs gained 260g/head/day over the course of the experiment.

Table 5. Liveweight gain and condition score of the experimental ewes and lambs before and after grazing.

	Pre-Grazing (21.6.2017)	Post Grazing (10.7.2017)	Change (kg/head)	Weight Gain/day (kg/head/day)
Ewe Weight (kg)	57.4	59.9	+2.5	0.15
Ewe Condition Score	2.2	2.6	+0.4	
Lamb Weight (kg)	21.1	25.4	+4.2	0.26

Ewes n=47 and Lambs n=40

4.2.4 Post grazing crop development

Following the end of the crop grazing period, the crop was monitored regularly by assigning the growth stages (according to the Zadoks decimal scale (Zadocks et al., 1974) to each treatment of each plot. The modal value of each treatment over the monitoring period is plotted in Figure 15. The general growth trends for both grazed and ungrazed treatments are the same. The grazed treatment is around one growth stage behind the ungrazed treatment for most of the period leading into harvest. The ripening of the grain occurs from GS90, which has nearly been reached by the ungrazed treatment (GS87) when the last measurements were taken, whereas the grazed treatment is only beginning to deposit protein and carbohydrates within the grain associated with the milk development stage (GS70).

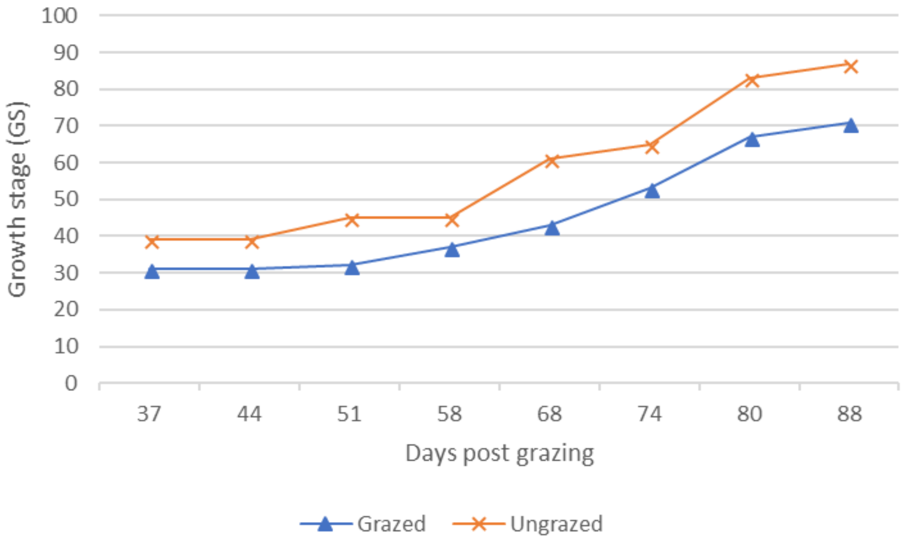


Figure 15. The crop growth stages (modal values from all plots per treatment, n = 25) from 15/08/2017 (37 days post-grazing) to 03/10/2017 (88 days post-grazing) for the grazed and ungrazed treatments comparing the crop development leading into harvest. The stages represented include stem elongation (GS30), booting (GS40), ear emergence (GS50), flowering (GS60), milk development (GS70), dough development (GS80), ripening (GS90) the final stage (Zadocks et al., 1974).

4.3 Livestock spatial grazing patterns of sheep grazing crops

4.3.1 Diurnal grazing behaviour

The diurnal activity demonstrated in Figure 16 shows a normal daily sheep pattern of activity. Grazing commences with sunrise around 6am with a peak morning graze ceasing at around 8am. Following this is a period of reduced activity throughout the middle of the day leading into an afternoon graze at 3-5pm ceasing with sunset at around 5pm. There is a late-night graze which we sometimes see in sheep (particularly lactating ewes and lambs) which occurred here at around 10pm.

Based on sheep behaviours, speeds greater than 0.05m/s were classed as grazing and those below 0.5m/s were categorised as resting. This resulted in a categorisation of 30-40% of the day being predicted as grazing. The analysis was separated into 3 periods: days 1-3 (start), days 7-9 (middle), days 13-15 (end) and plotted over the 24 hours (Figure 16).

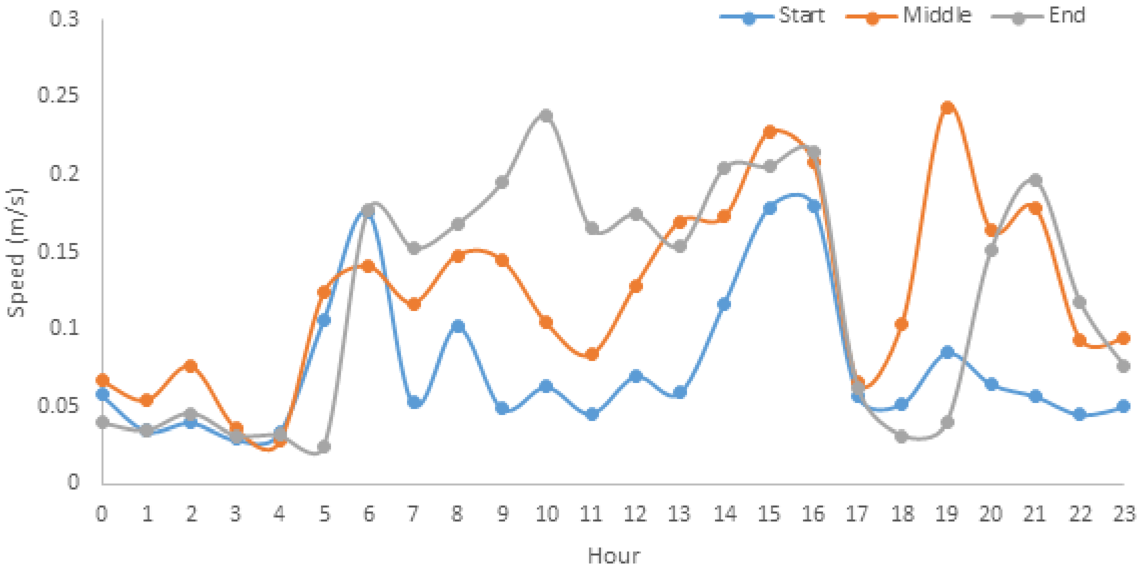


Figure 16. Diurnal activity pattern of the lactating ewes averaged across the trial period for the three grazing periods (days 1-3 (start), days 7-9 (middle), days 13-15 (end). There is an increase in activity throughout the middle period of the day as FOO decreases across the trial period.

4.3.2 Grazing and resting livestock residency index (LRI)

The maps shown in **Error! Reference source not found.Error! Reference source not found.** and **Error! Reference source not found.Error! Reference source not found.** are the Livestock Residency Index (LRI) maps across the entire trial period for grazing and resting behaviour, respectively. These are derived from the 20 GNSS collared animals. A LRI calculates the time animals spend in that particular 10x10m grid cell (GPS fixes) as a percentage of the total number of GPS fixes. The ensuing maps show a clear differentiation in grazing and resting locations with camping locations predominantly centred around the dam on the eastern boundary and along the southern paddock border. The grazing locations show a relatively even paddock distribution with a high residency nearby the camping locations. Breaking the trial down into 3 periods demonstrates a clear shift in spatial biomass utilisation throughout the crop grazing duration (**Error! Reference source not found.** and **Error! Reference source not found.**).

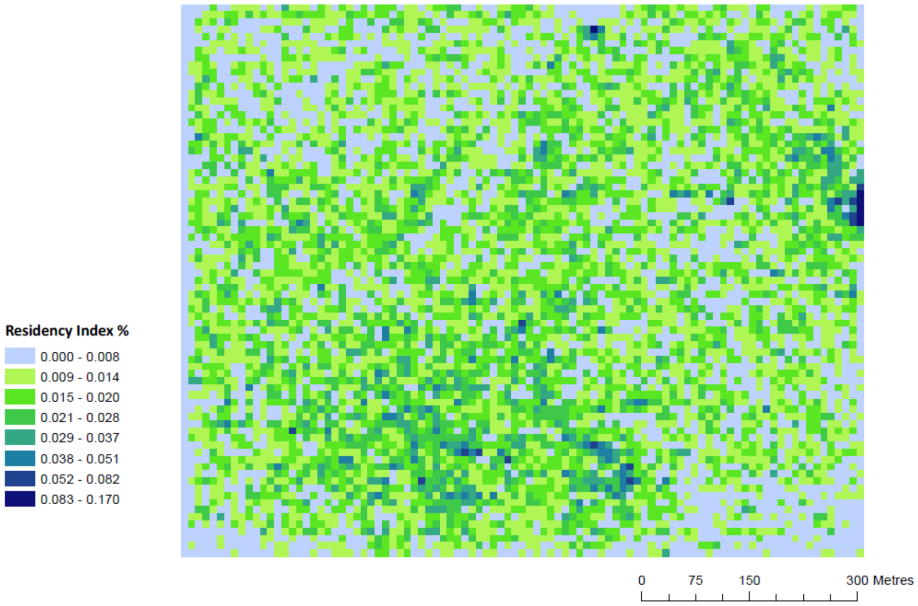


Figure 17. Grazing LRI across the entire trial period.

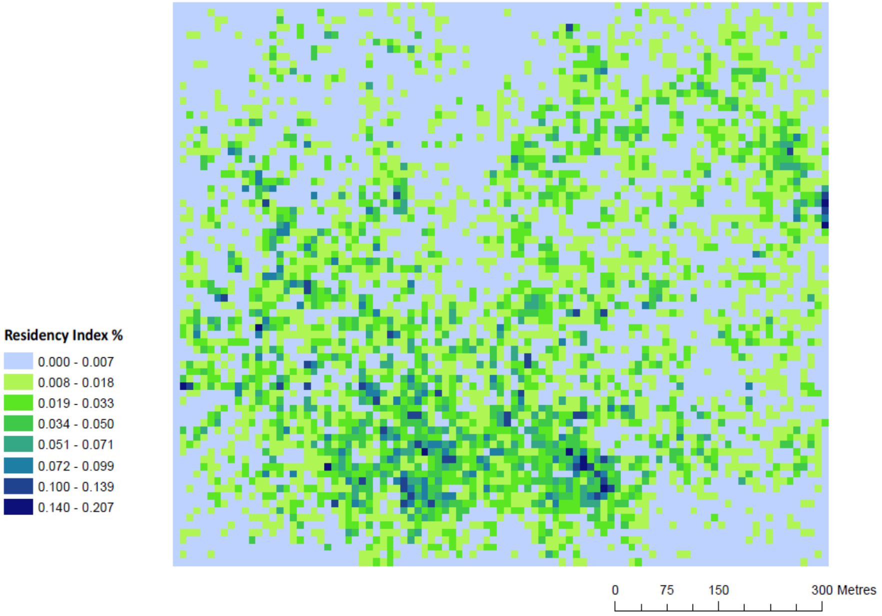


Figure 18. Resting LRI across the entire trial period.

There is a clear shift in the grazing locations across the trial period (Figure 19). Overall, the sheep utilised most of the paddock with there being a high density of grazing residency around the dominant camping locations. Some GPS error must also be factored in here which may result in some camping behaviour being misclassified as grazing. The first 3 days grazing are focused around the centre of the paddock. The middle 3 days grazing period sheep tend to move across to the western half of the paddock. The last 3 days shows an even grazing distribution across the paddock. This is most likely associated with declining levels of biomass and sheep travelling further and faster in search of available feed. There was no correlation between the LRI maps for the 3 grazing periods or 3 resting, indicating no similarity in grazing patterns between the three grazing periods. There was a correlation between the all days grazing and the last 3 days grazing LRI (r2=0.51). This finding indicates that the increase in time spent grazing in the last 3 days was moderately correlated to an increase in the all days grazing LRI also.

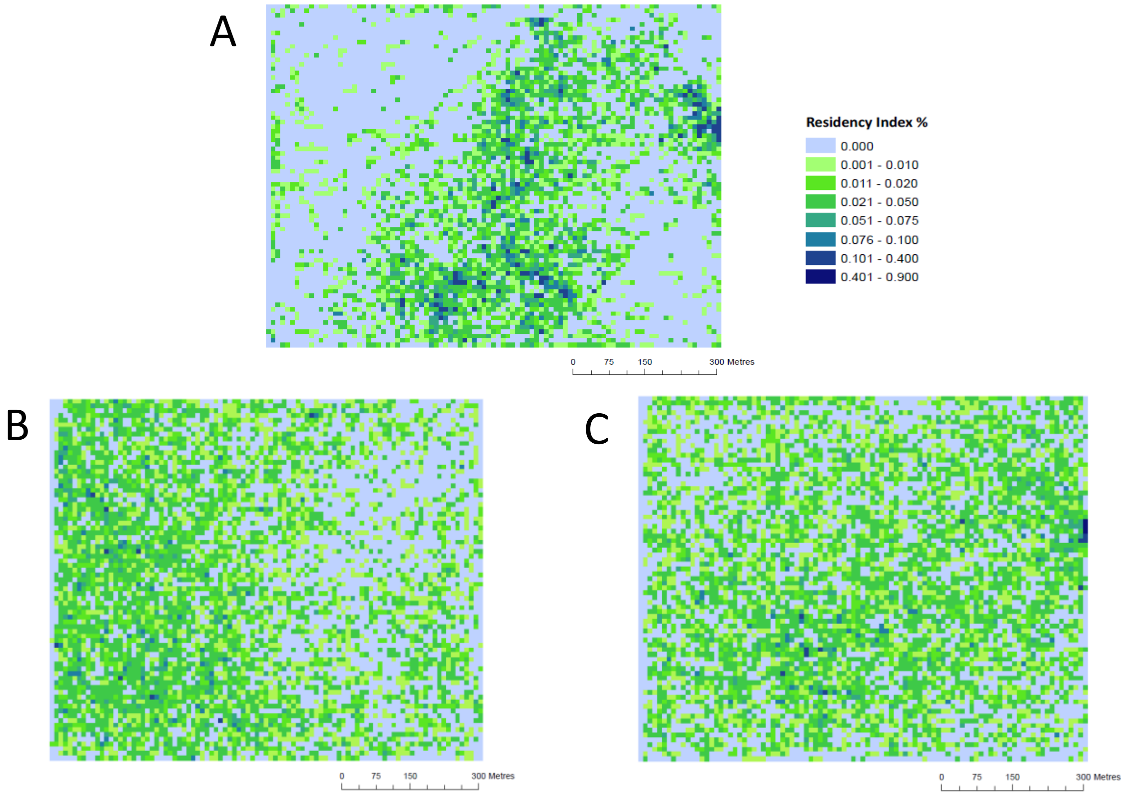


Figure 19. The Livestock Residency Index maps for the three grazing periods: Map A is the first 3 days (1-3), Map B is the middle 3 days (7-9) and Map C is the last 4 days (13-15).

The resting LRIs show a clear preference of camping locations, primarily around the eastern dam and the southern end of the paddock on higher ground. The change in resting locations across the paddock appear to follow the grazing locations in those time periods, going from central to western to lower half of the paddock.

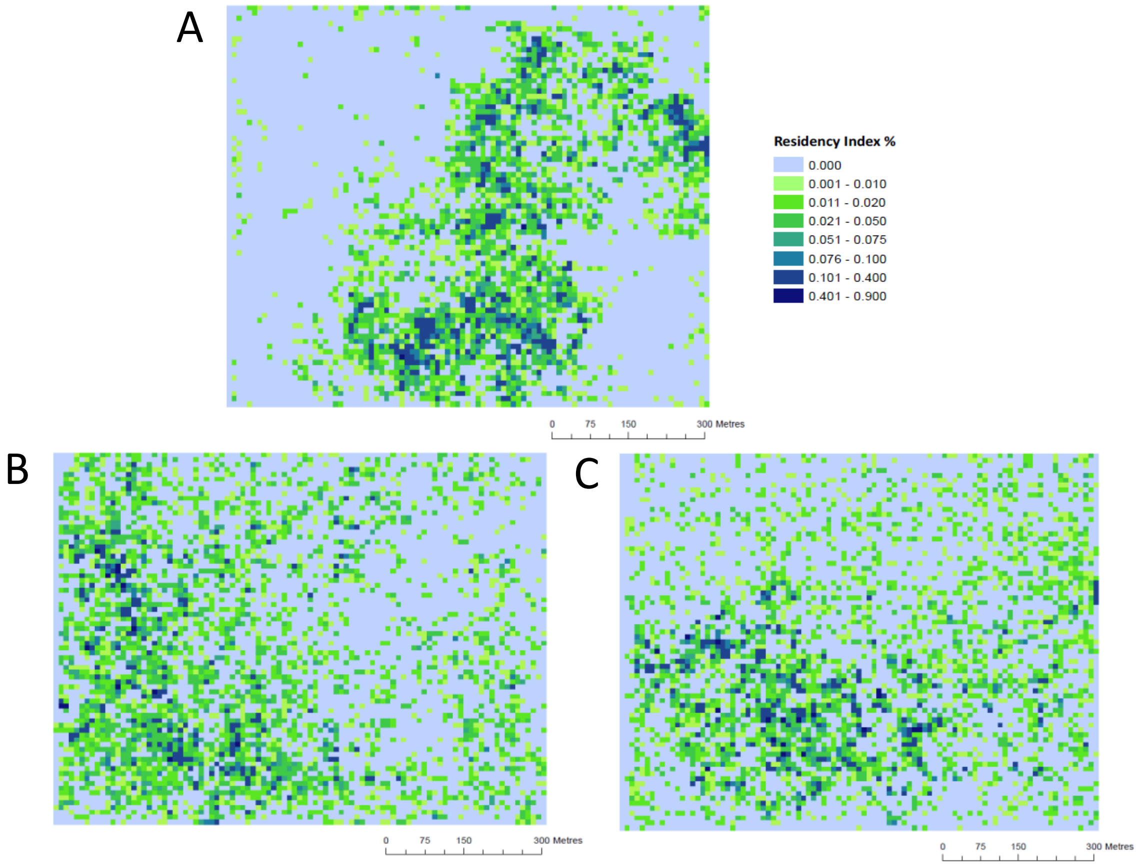


Figure 20. The Livestock Residency Index maps for the three resting periods: Map A is the first 3 days (1-3), Map B is the middle 3 days (7-9) and Map C is the last 4 days (13-15).

4.4 Paddock - Relationships between livestock spatial grazing patterns, soil, NDVI and yield measurements

To understand the spatial patterns across the trial site and the relationships between various sensor and soil measurements recorded, a whole paddock scale assessment was completed along with comparison between the 50 treatment sites (both grazed and ungrazed).

Table 6 details the regressions conducted between the various data layers available across the entire trial site. Multiple regressions were also run as part of this analysis with very little improvement to the original regression, hence have not been reported here. Figure 21 to Figure 27 visually demonstrate the relationships between yield and elevation, sheep LRI, EM38, thorium and NDVI.

The results in

Table 6 indicate the following:

1. There was a poor relationship between the soil quality measurements taken using EM38 and Thorium and the Livestock Residence Index over the 4 LRI time periods for grazing and resting. There was a significant trend between the variables as the P value of the regression was significant ($P<0.05$).
2. There was a poor relationship between the NDVI readings taken using the drone and the Livestock Residency Index over the 4 LRI time periods for grazing and resting. There was a

significant trend between the variables as the P value of the regression was significant ($P<0.05$).

3. There was a poor relationship between final grain yield and the Livestock Residence Index over the 4 LRI time periods for grazing and resting. There was a significant trend between the variables as the P value of the regression was significant ($P<0.05$).
4. There was a low-medium correlation between grain yield and the UAV F4 drone flight and the regression was significant ($r^2=0.19$, $P<0.001$).
5. There was a positive and significant correlation between the F3 and F4 UAV drone flights ($r^2=0.53$, $P<0.001$). There was no significant regression between any of the other drone flights.

Table 6. Regressions performed at the whole paddock scale.

Response variate (Y)	**Fitted term (x)**	**Equation**	**Adjusted R^2**	**RSD**	**F value**
Yield (t/ha)	All days grazing LRI(x)	y = 2733 + 8015x	0.014	578.12	<0.001
Yield (t/ha)	All days resting LRI(x)	y = 2812 + 2243x	0.005	580.76	<0.001
Yield (t/ha)	1st 3 days resting LRI(x)	y = 2846 - 263x	0.0003	582.15	0.177
Yield (t/ha)	1st 3 days grazing LRI(x)	y = 2848 - 4215x	0.0003	582.14	0.154
Yield (t/ha)	Middle 3 days grazing LRI(x)	y = 2796 + 3348x	0.0097	579.38	<0.001
Yield (t/ha)	Middle 3 days resting LRI(x)	y = 2827 + 1143x	0.0056	580.59	<0.001
Yield (t/ha)	Last 3 days grazing(x)	y = 2785 + 4228x	0.0136	578.15	<0.001
Yield (t/ha)	Last 3 days resting(x)	y = 2826 + 1180x	0.0084	579.68	<0.001
Yield (t/ha)	EM(x)	y = 2653 + 19.8x	0.0322	572.68	<0.001
Yield (t/ha)	Thorium(x)	y = 2881 - 4.93x	0.0025	581.39	<0.001
Yield (t/ha)	UAV F3 NDVI(x)	y = 2896 + 5056x	0.0838	557.2	<0.001
Yield (t/ha)	UAV F4 NDVI(x)	y = -122 + 5326x	0.1912	523.52	<0.001
All days grazing LRI	EM(x)	y = 0.014 - 0.000037x	0.0006	0.01	0.044
All days grazing LRI	UAV F4 NDVI(x)	y = 0.010 + 0.005x	0.0009	0.01	<0.001
All days grazing LRI	Thorium(x)	y = 0.0149 - 0.00016x	0.0131	0.01	<0.001
All days resting LRI	UAV F4 NDVI(x)	y = 0.020 - 0.011x	0.0009	0.02	<0.001
All days resting LRI	EM(x)	y = 0.0152 - 0.00015x	0.002	0.02	<0.001
All days resting LRI	Thorium(x)	y = 0.0163 - 0.00034x	0.0121	0.02	<0.001
1st 3 days grazing LRI	EM(x)	y = 0.0151 - 0.00017x	0.0016	0.02	<0.001
1st 3 days grazing LRI	UAV F4 NDVI(x)	y = 0.0331 - 0.035x	0.0053	0.02	<0.001
Middle 3 days grazing LRI	EM(x)	y = 0.0123 + 0.00015x	0.0023	0.02	<0.001
Middle 3 days grazing LRI	UAV F4 NDVI(x)	y = 0.0060 + 0.013x	0.0015	0.02	<0.001
Last 3 days grazing LRI	EM(x)	y = 0.0142 - 8.27E-05x	0.0007	0.02	0.021
Last 3 days grazing LRI	UAV F4 NDVI(x)	y = 0.0063 + 0.0128x	0.0015	0.02	<0.001
EM	UAV F3 NDVI(x)	y =9.54 + 0.133x	0	5.26	0.942
EM	UAV F4 NDVI(x)	y = 8.087 + 2.62x	0.0006	5.26	0.042
Thorium	UAV F4 NDVI(x)	y = 13.9 - 11.15x	0.0082	5.87	<0.001
F3 UAV NDVI	UAV F4 NDVI(x)	y = -0.29 + 0.50x	0.5321	0.02	<0.001

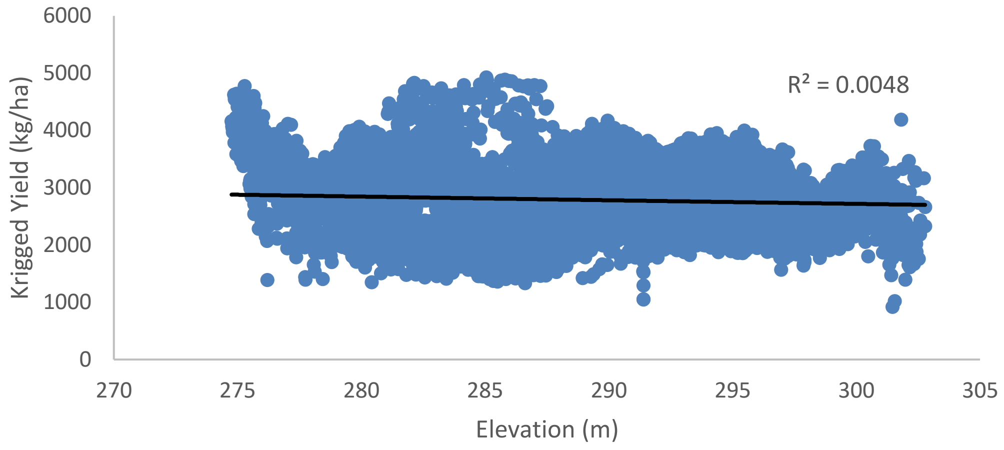


Figure 21. Residual plot for elevation (x-variable) and grain yield (response variate), showing a low correlation (r^2=0.0048) using all paddock data.

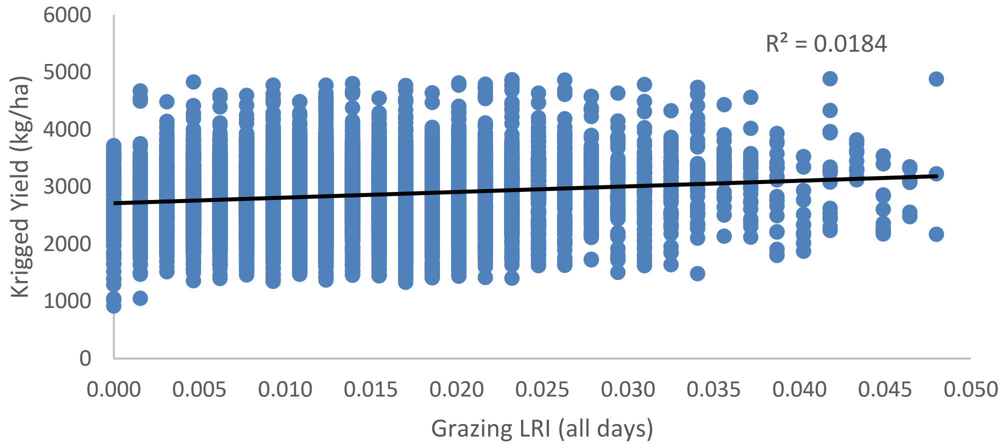


Figure 22. Residual plot for all days grazing LRI (x-variable) and grain yield (response variate), showing a low correlation (r^2=0.0184) using all paddock data.

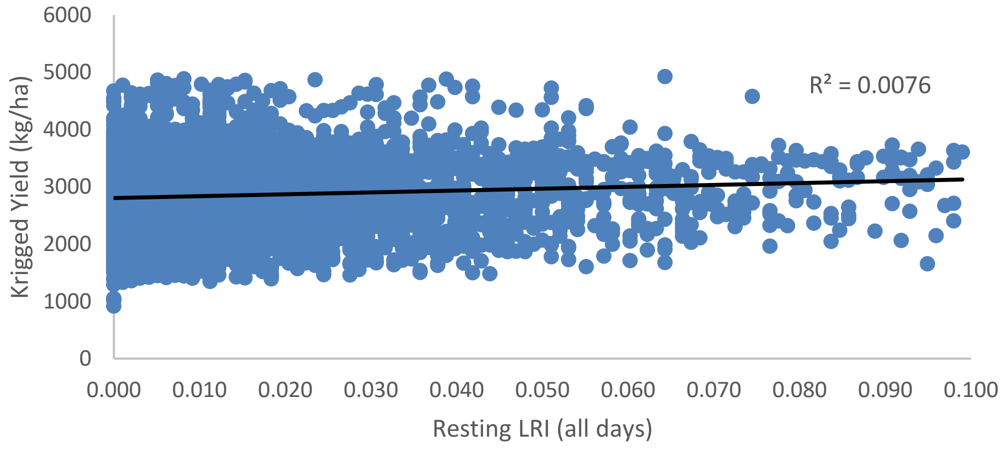


Figure 23. Residual plot for all days resting LRI (x-variable) and grain yield (response variate), showing a low correlation (r^2=0.0076) using all paddock data.

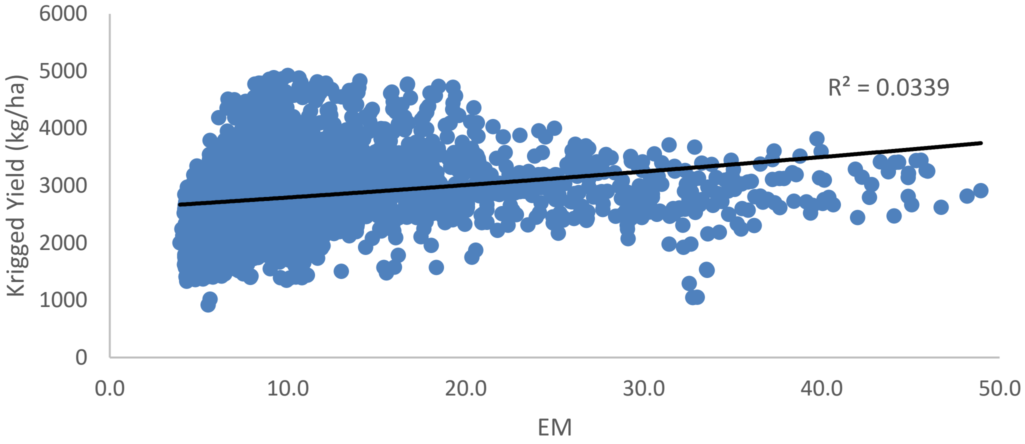


Figure 24. Residual plot for EM (x-variable) and grain yield (response variate), showing a low correlation (r^2=0.0339) using all paddock data.

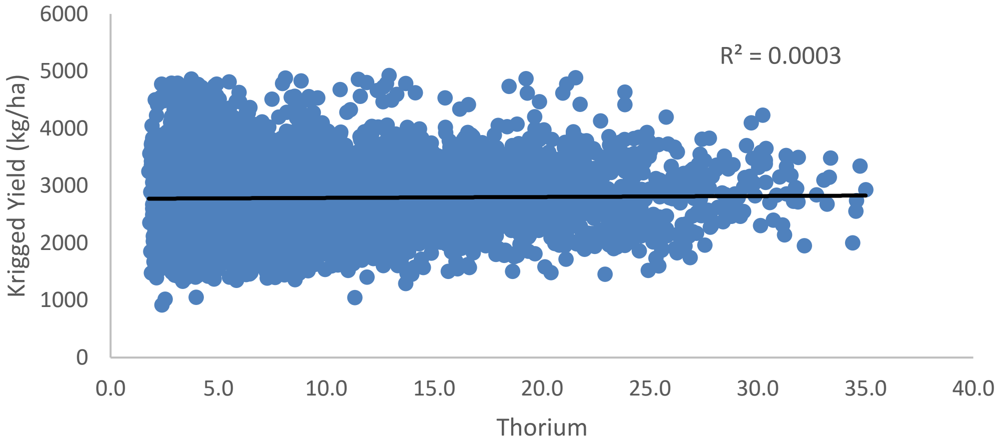


Figure 25. Residual plot for Thorium (x-variable) and grain yield (response variate), showing a low correlation (r^2=0.0003) using all paddock data.

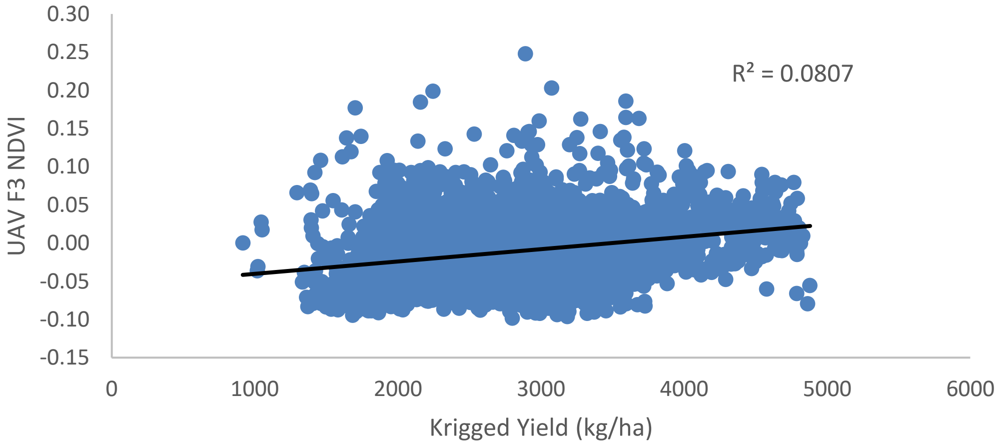


Figure 26. Residual plot for grain yield (x-variable) and UAV F3 NDVI (response variate), showing a low correlation (r^2=0.0807) using all paddock data.

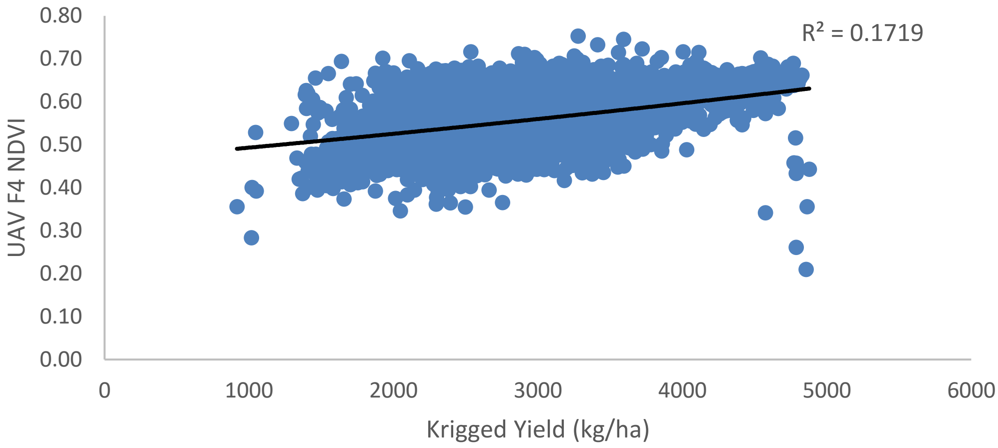


Figure 27. Residual plot for grain yield (x-variable) and UAV F4 NDVI (response variate), showing a positive correlation (r^2=0.172) using all paddock data.

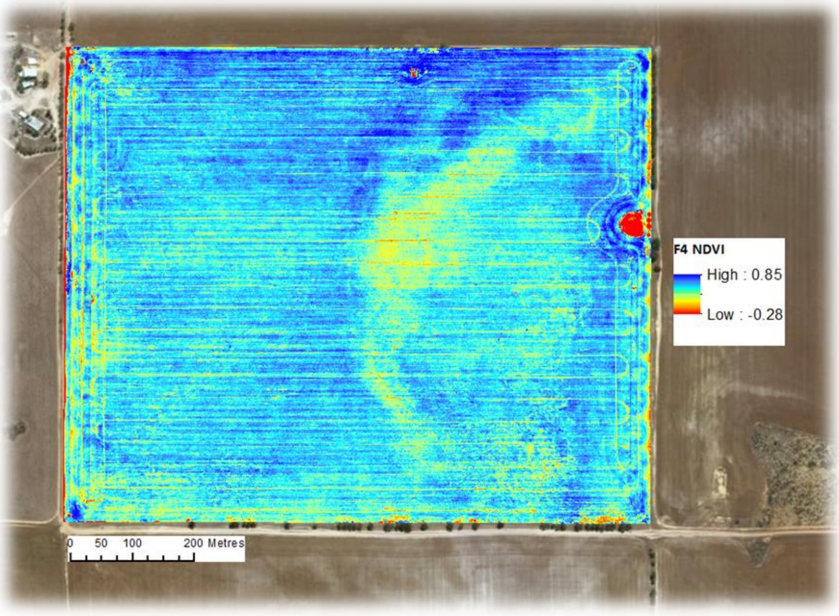


Figure 28. F4 UAV NDVI map. Visual comparison with the grain yield map (Figure 14) shows similarities between NDVI and yield.

4.5 Sites - Use of sensor tools to predict biomass, harvest grain quality, nutritive value

4.5.1 Predicting feed-on-offer (FOO)

The regression analyses performed at the treatment sites are summarised in

Table 7. The response variate Greenseeker without stubble (GS NoSt) was consistently the most significant term in the regression analyses with GS NoSt the only significant predictor of FOO (kg

DM/ha) in the pooled data set regression analysis (R^2 = 0.89, F <.001); the post grazing (grazed + ungrazed) data set regression analysis (R^2 = 0.87, F<.001), and the post grazing ungrazed regression analysis (R^2 = 0.70, F<.001). The accuracy of GS NoSt to predict the available FOO (kg DM/ha) is much better in the pooled data set with an RSD of 55.96kg DM/ha compared to the post grazing data set which had a higher RSD of 68.07kg DM/ha. However, height as a second significant term, in addition to GS NoSt, resulted in a significant regression model for available FOO (kg DM/ha) from the pre-grazing data set (R^2 = 0.75, F<.001) and a fairly accurate prediction with a low RSD of 14.76kg DM/ha. Interestingly, height did not have any significance in any of the other data sets which would imply that it has a strong relationship with biomass (as FOO kg DM/ha) only during the early vegetative growth stages. The only other sensor that resulted in a significant, however weak, regression with FOO (kg DM/ha) was Landsat 8 NDVI as a second significant term, in addition to GS NoSt in the post grazing grazed data set (R^2 = 0.26, P = 0.019).

The results from the FOO (kg DM/ha) regression analyses indicate that the Greenseeker (using the different data sets) was able to detect the changes in biomass due to crop development and grazing, however, at low biomass levels (such as when using the grazed plot data only) the ability to accurately predict the available FOO (kg DM/ha) drastically reduced.

4.5.2 Use of sensors to predict above ground crop biomass post grazing

The above ground biomass (AGB t/ha) regression analyses from the harvest data set resulted in several significant regressions (

Table 7). The regression that included UAV F5 and PG-Landsat NDVI readings as significant terms for AGB (t/ha) in the ungrazed harvest data set was the improved model with R^2 = 0.77 (F<.001) and an RSD of 0.80t/ha, compared to the regression with only UAV F5 as the predictor of AGB (t/ha) with R^2 = 0.73 (F<.001) and an RSD of 0.88t/ha. Similarly, UAV F5 and PG-Landsat resulted in the improved regression (R^2 = 0.59) for predicting AGB (t/ha) in the combined harvest data set (grazed + ungrazed) compared to UAV F5 as the sole predictor (R^2 = 0.56). The analysis with the grazed harvest data set resulted in a significant (P = 0.002) but weak regression with UAV F5 as the significant term (R^2 = 0.36).

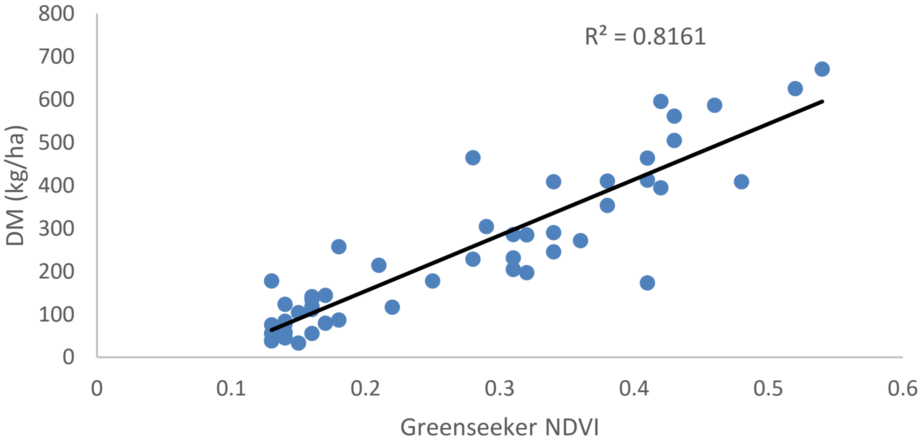


Figure 29. Post grazing biomass and Greenseeker measurements including both the grazed and ungrazed sites.

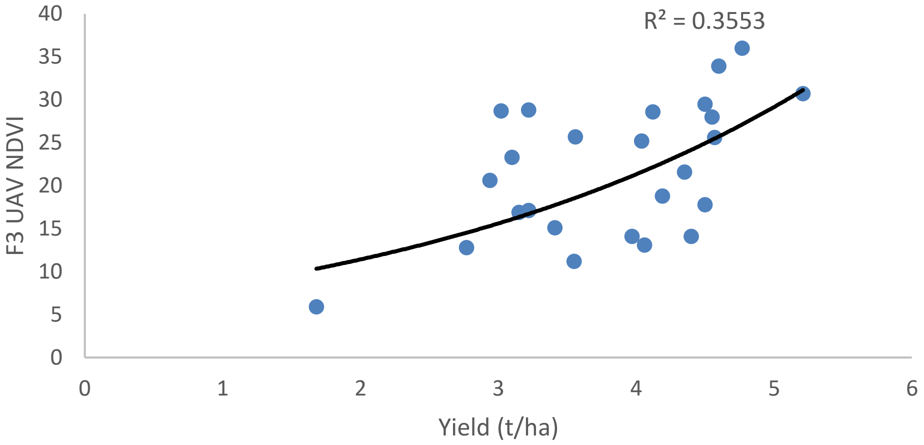


Figure 30. Residual plot for grain yield (x-variable) and UAV F3 NDVI (response variate), showing a low correlation (r^2=0.3553) for the ungrazed site data.

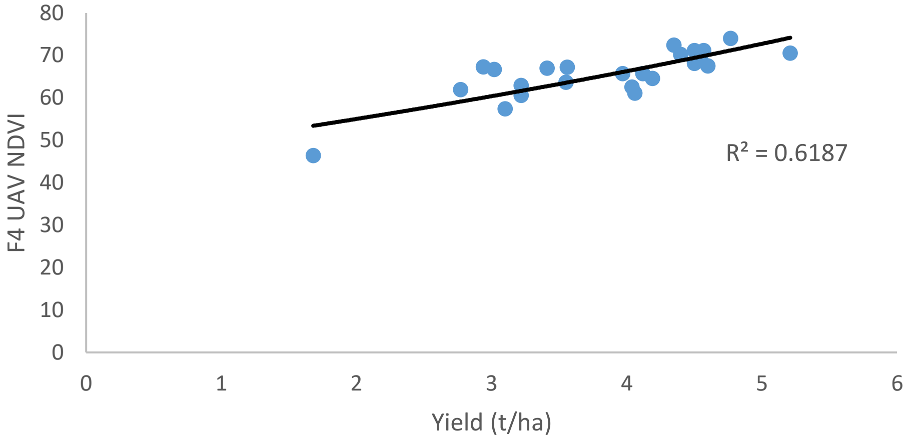


Figure 31. Residual plot for grain yield (x-variable) and UAV F4 NDVI (response variate), showing a high correlation (r^2=0.6187) for the ungrazed site data. Note this has 1 outlier removed.

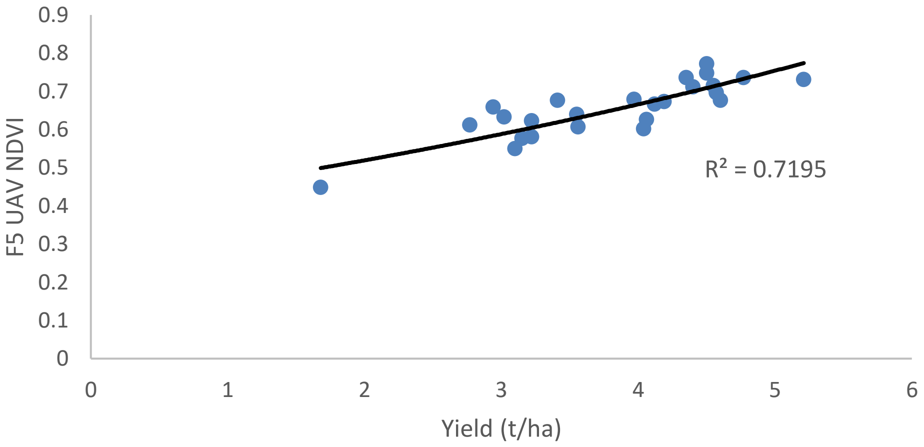


Figure 32. Residual plot for grain yield (x-variable) and UAV F5 NDVI (response variate), showing a high correlation (r^2=0.7195) for the ungrazed site data.

Figure 30, Figure 31 and Figure 32 above show a higher value if using late season NDVI measurements for yield prediction whilst early season NDVI is poorly correlated with final yield.

4.5.3 Grain yield and protein

AGB (t/ha) was the strongest predictor of yield (t/ha) with a R^2 of 0.95 (F <.001) and an RSD of 0.19 using the combined harvest data set (ungrazed + grazed). Further, UAV F5 was the only sensor as a significant term in the regression analyses against grain yield (t/ha) from the different data sets (

Table 7). The ungrazed harvest data set resulted in the strongest regression with a R^2 of 0.70 (F<.001) and the RSD of 0.45t/ha. The combined harvest (ungrazed + grazed) and grazed harvest data sets resulted in significant however weak regressions with R^2 of 0.58 (F<.001) and R^2 of 0.31 (F = 0.003) respectively. PG-Height (cm) was the only significant term (R^2 = 0.42, F<.001) for the regression analysis against grain %CP from the combined harvest data set (ungrazed + grazed). The regression analyses using the ungrazed and grazed harvest data sets against grain %CP resulted in no significant regressions.

4.5.4 Use of sensors to predict forage quality

The forage %CP and IVDMD regression analyses resulted in significant but weak regressions (R^2 = 0.59, F=0.039 and R^2 = 0.33, F=0.047 respectively), with the significant fitted term for IVDMD the calculated FOO (kg DM/ha) with an RSD of 2.90. The %CP regression included GS NoSt and FOO (kg DM/ha) as significant terms. However, height as a marginally non-significant term (F = 0.052) was required for the regression to remain significant. Removing FOO (kg DM/ha) from the regression analyses using the forage data sets resulted in no significant regressions. The small sample size (n=10) for the forage regression analyses was perhaps a contributing factor to not being able to investigate the relationships between variates adequately, considering that using FOO (kg DM/ha) is not the most appropriate predictor.

4.5.5 The use of Satellite (Sentinel, Landsat 8) NDVI and UAV NDVI to predict biomass and forage qualities

The Sentinel NDVI data were used in the regression analyses against FOO (kg DM/ha) from the pre-grazing data set, and the forage %CP and IVDMD from the forage data set, but did not result in any significant regressions inclusive of Sentinel NDVI. The post grazing UAV data was included in the regression analyses against post grazing FOO (kg DM/ha) using the post grazing data sets, with no significance. However, Landsat 8 was a significant term in the regression against FOO (kg DM/ha) as mentioned above. Additionally, the UAV and Landsat 8 post-grazing data was included in the regression analyses against AGB (t/ha), grain yield (t/ha) and grain protein (%CP) using the harvest data set but was not significant terms for any of these regressions. These results, in addition to the correlation analysis, indicate that the NDVI readings from the sentinel during the early vegetative growth stage of the crop had a very small relationship with FOO (kg DM/ha), forage %CP and forage IVDMD (R^2 = 0.11, R^2 <.001, R^2 = 0.008 respectively). Additional sentinel data to correspond with the post grazing and/or the harvest data sets would have allowed a more thorough investigation into the possible relationships between sentinel NDVI and crop parameters.

Table 7. Regression analyses performed using data from the 50 treatment sites. The corresponding data from the grazed and ungrazed sites along with the time of collection (pre-grazing, post-grazing and harvest) used for each regression is listed under the data set column.

Response variate	Fitted term/s (x)	Equation	Adjusted R^2	RSD	F value	Data set
FOO (kgDM/ha)	GS NoSt(x)	$y = -150.7 + 1436.7x$	0.89	55.96	<0.001	Post-grazing & pre-grazing (grazed + ungrazed)
FOO (kgDM/ha)	GS NoSt(x)	$y = -152.9 + 1446.7x$	0.87	68.07	<0.001	Post-grazing (grazed + ungrazed)
FOO (kgDM/ha)	GS NoSt(x)	$y = -261.1 + 1718x$	0.7	80.51	<0.001	Post-grazing (ungrazed)
FOO (kgDM/ha)	GS NoSt(x_1) + Landsat(x_2)	$y = 340 + 1067x_1 - 15.38x_2$	0.26	45.33	0.019	Post-grazed (grazed)
FOO (kgDM/ha)	GS NoSt(x_1) + Height(x_2)	$y = -72.9 + 707x_1 + 3.083x_2$	0.75	14.76	<0.001	Pre-grazing
AGB (t/ha)	UAV F5(x)	$y = -4.85 + 0.193x$	0.73	0.88	<0.001	Harvest (ungrazed)
AGB (t/ha)	UAV F5(x)	$y = -3.26 + 0.174x$	0.36	1.37	0.002	Harvest (grazed)
AGB (t/ha)	UAV F5(x)	$y = -3.36 + 0.1728x$	0.56	1.14	<0.001	Harvest (grazed + ungrazed)
AGB (t/ha)	UAV F5(x_1) + Landsat(x_2)	$y = -13.21 + 0.2013x_1 - 0.296x_2$	0.77	0.8	<0.001	Harvest (ungrazed)
AGB (t/ha)	UAV F5(x_1) + Landsat(x_2)	$y = -10.33 + 0.1773x_1 + 0.254\ x_2$	0.59	1.11	<0.001	Harvest (grazed + ungrazed)
Yield (t/ha)	AGB(x)	$y = 0.113 + 0.4898x$	0.95	0.19	<0.001	Harvest (grazed + ungrazed)
Yield (t/ha)	UAV F4(x)	$y = -3.41 + 0.11x$	0.62	0.51	<0.001	Harvest (ungrazed sites)
Yield (t/ha)	UAV F5(x)	$y = -2.310 + 0.0936x$	0.7	0.45	<0.001	Harvest (ungrazed)
Yield (t/ha)	UAV F5(x)	$y = -2.009 + 0.0887x$	0.58	0.57	<0.001	Harvest (grazed + ungrazed)
Yield (t/ha)	UAV F5(x)	$y = -1.40 + 0.078x$	0.31	0.67	0.003	Harvest (grazed)
Yield (t/ha)	EM38(x_1) + Thorium(x_2) + UAV F2(x_3) + UAV F3(x_4) + UAV F4(x_5) + UAV F5(x_6)	$y = -1.6 + 0.015x_1 - 0.006x_2 + 0.03x_3 + 0.0005x_4 - 0.007x_5 + 8.4x_6$	0.77	0.02	<0.001	Harvest (ungrazed)
Yield (t/ha)	EM38(x_1) + Thorium(x_2)	$y = 3.5+0.04x_1 - 0.0064x_2$	0.08	0.35	0.43	Harvest (ungrazed)
Yield (t/ha)	UAV F2(x_1) + UAV F3(x_2) + UAV F4(x_3) + UAV F5(x_4)	$y = -1.54 + 0.029x_1 + 0.0031x_2 - 0.019x_3 + 9.51x_4$	0.76	1.26	<0.001	Harvest (ungrazed)
Yield (t/ha)	FOO (kgDM/ha)(x)	$y = 2.86 + 0.002x$	0.2	0.73	0.024	Post-grazing & harvest (grazed + ungrazed)
Yield (t/ha)	FOO (kgDM/ha)(x)	$y = 2.2 + 1.61x$	0.22	0.67	0.016	Post-grazing & harvest (ungrazed)
Yield (t/ha)	EM38(x)	$y = 3.42 + 0.041x$	0.09	0.79	0.153	Harvest (ungrazed)
Yield (t/ha)	GS NoSt(x)	$y = 2.65 +3\ .12x$	0.09	0.78	0.146	Post-grazing & harvest (ungrazed)
Yield (t/ha)	Thorium(x)	$y = 3.71 + 0.013x$	0.01	0.82	0.66	Harvest (ungrazed)
GS NoSt	UAV F2(x)	$y = 0.296 + 0.0065x$	0.34	0.06	0.003	Post-grazing (ungrazed)
UAV F5	UAV F4(x)	$y = -0.101 + 0.011x$	0.86	0.03	<0.001	(ungrazed)
Grain %CP	PG Height(x)	$y = 9.019 - 0.05775x$	0.42	0.73	<0.001	Harvest (grazed + ungrazed)
Forage %CP	GS NoSt(x_1) + FOO(x_2) + Height(x_3)	$y = 19.22 + 78.2x_1 - 0.686x_2 + 0.354x_3$	0.59	1.08	0.039	Pre-grazing
Forage IVDMD	FOO (kgDM/ha)(x)	$y = 68.42 + 0.0826x$	0.33	2.9	0.047	Pre-grazing

Where, FOO (kgDM/ha) is the dried biomass samples converted to kg/ha, AGB(t/ha) is the above ground biomass at harvest, Grain %CP and Forage %CP are the crude protein percentages for the grain and forage (pre-grazing) respectively, Forage IVDMD is the in vitro dry matter digestibility of the forage prior to grazing and GS NoSt are the Greenseeker readings with all stubble removed from the quadrant.

4.5.6 The impact of stubble on Greenseeker NDVI readings

The presence of stubble within the measuring quadrant influenced the Greenseeker NDVI readings at both pre-grazing and post-grazing. The stubble biomass (g) is depicted in Figure 33 as the lightly shaded areas. Once the stubble had been removed the Greenseeker readings increased (point 1 to point 2), more so at pre-grazing (blue line in Figure 33), but still evident with the ungrazed treatment at post-grazing (orange line). Further, the rate of which the Greenseeker NDVI decreased, followed a similar rate of decrease as the fresh biomass (dark shaded areas) when sequential cuts were taken from point 2 onwards.

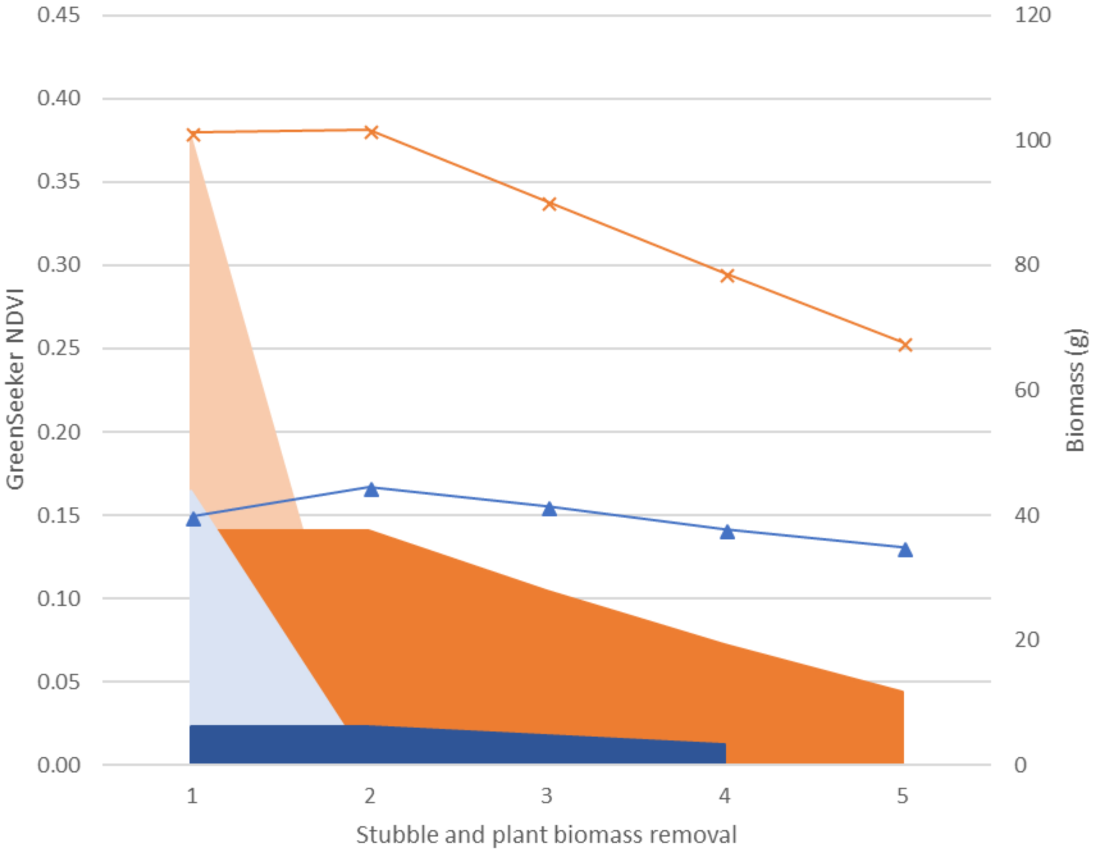


Figure 33. The pre-grazing (blue) and post-grazing (orange) NDVI readings at different stages of biomass removal (shaded areas). The lightly shaded areas represent the stubble with the darker areas representing the fresh biomass. The post-grazing data represented here are from the ungrazed treatment.

4.5.7 Relationships between sensor technologies

The data from different NDVI sensing platforms were used to investigate whether any relationships between sensors existed. The available sensors using the pre-grazing data set were the Greenseeker and Sentinel, which correlated poorly with a R^2 of 0.11. Sensor data at post grazing came from the Greenseeker, UAV and Landsat 8 which resulted in poor correlations between all three sensors. The UAV sensor was unable to give an exact NDVI value for the grazed plots. Therefore correlations between the UAV and the other sensors were performed for the ungrazed treatment only: UAV and Greenseeker ($R^2 = 0.42$), and UAV and Landsat 8 ($R^2 = 0.14$). The full post grazing data (both grazed and ungrazed cage data) set was used for the correlation between Landsat 8 and Greenseeker which resulted in no relationship ($R^2 < 0.001$) between the two sensors.

The fifth UAV flight (UAV F5) was the only sensor with data towards the end of the growing season, which only allowed for correlations to be done with data from earlier in the season. UAV F5 is poorly correlated to all the NDVI sensors from the post grazing data set with R^2 of 0.29 against post grazing UAV, R^2 of 0.19 against post grazing Greenseeker, and R^2 of 0.009 against post grazing Landsat 8.

4.6 Cost benefit analysis of crop grazing

The actual physical and financial performance of the grazed paddock was compared to the predicted performance of the paddock if it had been left ungrazed. Crop yield was significantly (17%) lower in the grazed treatment, however, grain price was significantly higher (11%) due to a better grain quality classification. The lower yield resulted in grain income being 7% lower in the grazed scenario. However, additional income from lamb liveweight gain when grazing the crop with ewes and lambs meant the grazed scenario produced a 2% higher total income. Gross Margin was 8% higher in the grazed vs the ungrazed scenario assuming paddock went Feed Barley or -8% if paddock went Malt Barley.

Table 8. Summary of the income and expenses for the grazed and ungrazed (hypothetical) scenario.

Grazed	
Lambs weight gain (kg)	1828
Lamb weight gain value	$ 4,524.30
Ewes weight gain (kg)	927
Ewe weight gain value	$ 1,376.60
Grain Yield (tonnes)	206
Income - Grain ($237/tonne)	$ 48,792.62
Income - Lambs + Grain	$ 53,316.92
Income- Ewes + Lambs + Grain	$ 54,693.51
Paddock expenses	$ 14,820.19
Grain GM	$ 33,972.43
Paddock GM (grain + lambs - paddock expenses)	$ 38,496.73
Potential Predicted if ungrazed	
Grain Yield (tonnes)	245
Income - Grain ($213/tonne)	$ 52,290.36
Income - Grain ($237/tonne)	$ 58,157.91
Grain GM (assuming feed barley)	$ 37,470.17
Grain GM (assuming malt barley)	$ 43,337.72
Supplementary feed costs	$ 1,867.00
Paddock GM (MALT grain - sup feed costs - paddock expenses)	$ 41,470.72
Paddock GM (FEED grain - sup feed costs - paddock expenses)	$ 35,603.17

Table 9. Summary of the difference and change in outputs received between the grazed and ungrazed scenarios

Factor	Grazed	Ungrazed	Change
Grain Yield (tons)	206	245	-17%
Grain Price ($/t)	237	213	+11%
Grain Income ($)	48,793	52,290	-7%
Lamb Income ($)	4,524	0	
Total Income ($)	53,317	52,290	+2%
Grain Production Cost ($)	14,820	14,820	-
Gross Margin ($)	38,497	35,603 (feed Barley) or 41,470 (malt Barley)	+8% -8%

Figure 34 to Figure 36 demonstrate the paddock profit maps on an individual 10x10m pixel level, allowing the identification of zones within the paddock which held the highest profitability value. What is clear within these maps is that grain yield is driving the high production areas with a small influence from sheep grazing locations.

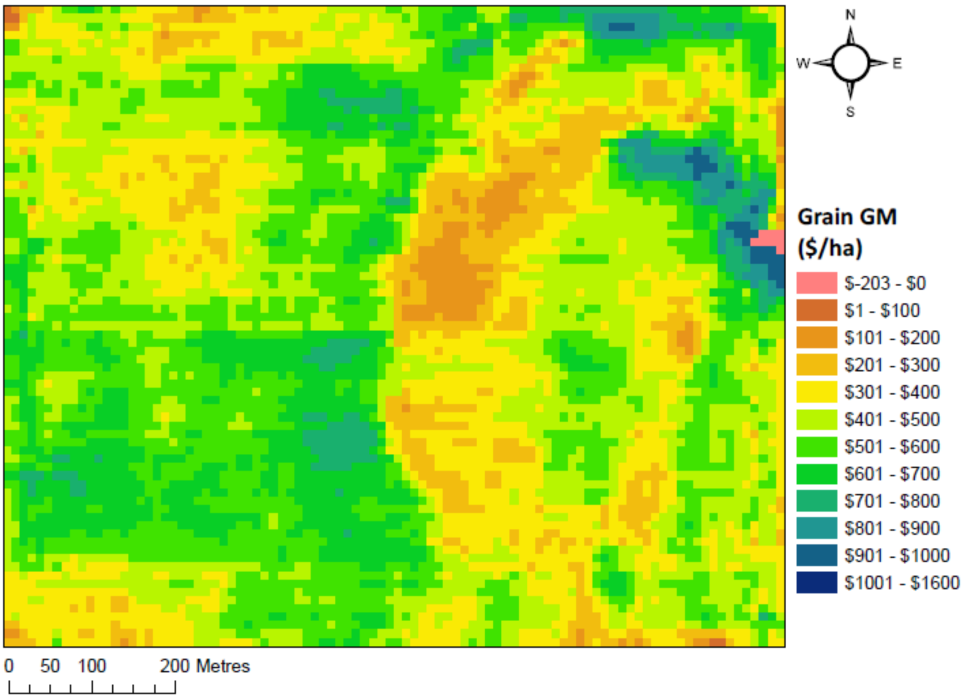


Figure 34. Barley grain yield gross margin (income - costs) for the grazed scenario. This results in a paddock gross margin (grain only) of $**33,972.**

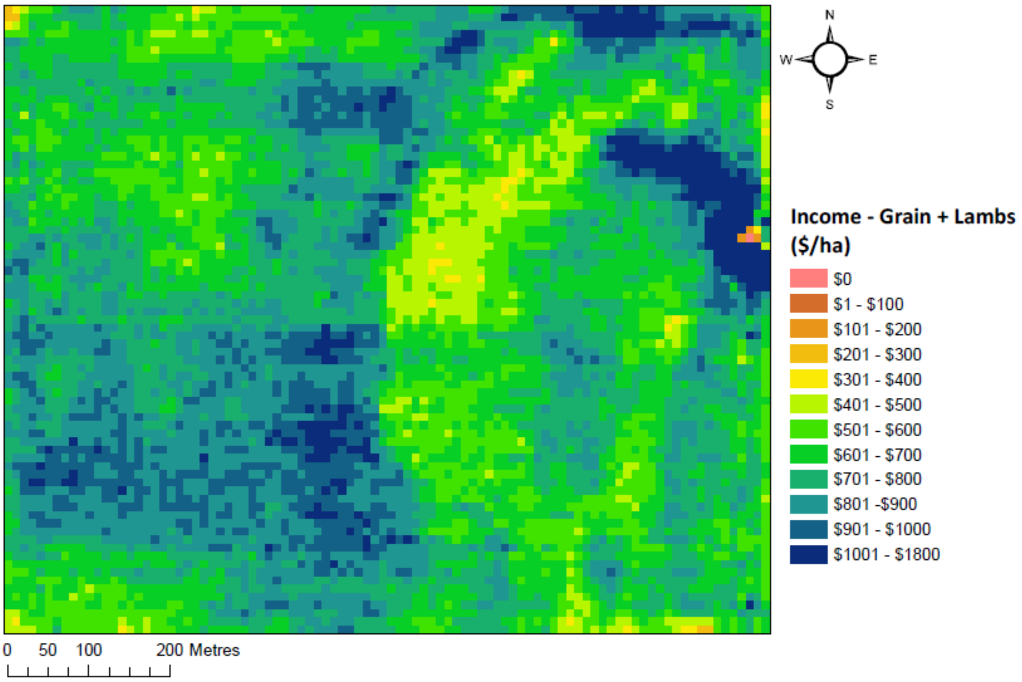


Figure 35. Total paddock income including grain yield and lamb weight gain distributed across the LRI map for the entire grazing period (valued at $2.48/kg). This equates to a total paddock income of **$53,316.**

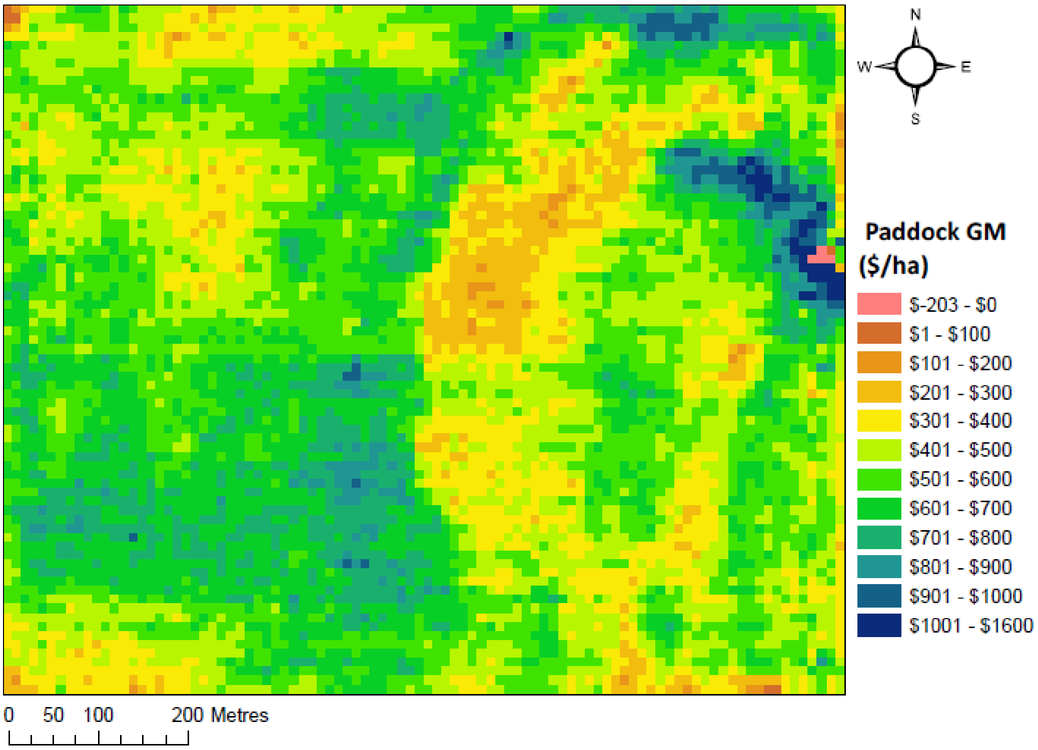


Figure 36. Total paddock gross margin including grain income, lamb weight gain income less grain expenses. This results in a total paddock gross margin of **$38,497**.

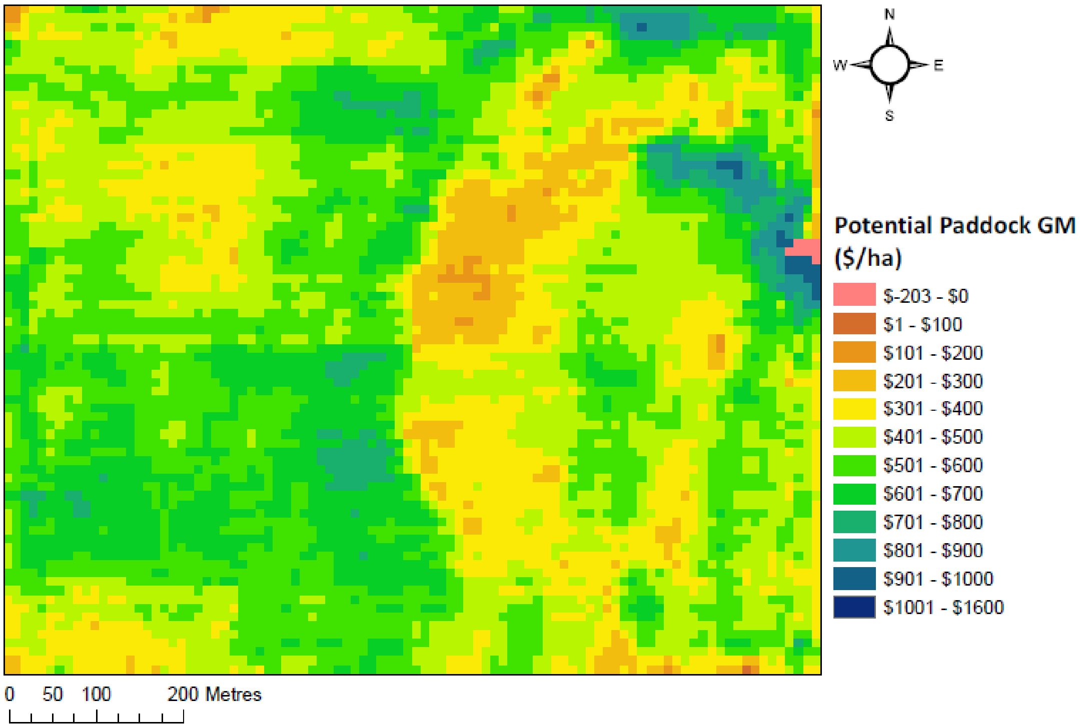


Figure 37. The potential paddock gross margin based on grain income (priced as feed barley, $213.17/tonne), a blanket increase of 0.54t/ha in yield due to being ungrazed, less grain costs and a supplementary feed cost of $1867 to feed ewes and lambs for the corresponding time period they were grazed on the crop. This equates to a total paddock gross margin of **$35,603.**

5. Discussion

5.1 Crop and animal performance

This experiment was conducted during the 2017 growing season which started with very dry conditions in May and June, and received above average rainfall from early July till the end of September (Figure 2). From early September to harvest, the grain-finishing period was ideal with very cool and frost-free temperatures received. The poor rainfall at the start significantly reduced crop and pasture growth thus delaying the start of crop grazing and significantly reducing the amount of crop biomass available for grazing. Better growing conditions prior to grazing would potentially have allowed for better animal production (higher live weight gain over a longer grazing period) and better crop recovery from grazing (earlier start and end of grazing and higher biomass at the end of grazing). However, the 'soft-finish' in September and October and the adequate rainfall from July onwards allowed the paddock to recover and produce an above average yield for this farm. Had the conditions during grain fill been less than ideal the yield differences between the plots may have been higher.

The grain yield and quality differences observed in this trial are reasonably consistent with results obtained from other crop grazing experiments conducted in Western Australia and nationally (Kirkegaard et al., 2015; Nicholson et al., 2016). The 17% reduction in grain yield from grazing is at the upper end of differences observed, but the level of crop biomass remaining at the end of grazing was very low (0.1 tonne DM/ha). A common observation by all members of the research team, was that the paddock had been very heavily and evenly grazed, beyond what is commonly recommended. Crop biomass at the end of grazing and the date of stock removal are key determinants of crop recovery after grazing and in the case of this experiment, the grazed plots did not recover to the same level as the ungrazed plots and resulted in the yield differences. The grain protein differences were also consistent with other research and a result of yield dilution (Frischke, Hunt, McMillan, & Browne, 2015).

The biomass value of 0.4t DM/ha for the ungrazed plots at the time of sheep removal from the crop was low as the property had received well below average rainfall to date. In a different season the biomass for the ungrazed plots could be around 1t DM/ha (Dove & Kirkegaard, 2014; Nicholson et al., 2016) and therefore the potential for an increased grazed plot biomass at the time of sheep removal which may have resulted in differing results to those observed and discussed below.

The liveweight and condition score change of the ewes and lambs over the two week crop grazing period was consistent with other research (Nicholson et al., 2016). The ewes gained on average 2kg and half a condition score. These highly positive results are indicative of the high nutritive value and digestibility of the crop (Table 3) which is above that observed in commercially available pellets and grain (Hyder & Curnow, 2016). As there is no research available to quantify the intake of crop during the two week period to guide producers, it is difficult to incorporate crop grazing into an overall farm feed budget and gauge possible liveweight gains achievable when grazing crops. Spatial grazing technologies such as accelerometers could play a significant role in future research to understand intake and allow for feed budgeting.

The original intention of this project was to compare the weight gains for ewes and lambs on the crop compared to pasture/supplementary feed and follow the lambs through to slaughter. However, the delay in the start of grazing and animal welfare considerations resulted in only one mob available for the experiment. There have not been any trials done to understand the impact of crop grazing on weaning weight, time to slaughter and carcass attributes. It is highly recommended that this assessment be conducted, as anecdotally lambs from ewes grazed on crops have been observed to reach slaughter weights faster and have better carcass quality.

5.2 The spatial grazing patterns of sheep grazing crops

This experiment has demonstrated that the spatial grazing patterns of sheep and lambs on crops varied over the period of grazing. However, these grazing patterns were unrelated over the 3 separate grazing periods demonstrated across the course of the experiment. Over the first 3 days, the grazing pattern was highly concentrated in certain areas but by the last 3 days there was an even distribution of grazing across the paddock. Similar results have been reported in cattle grazing pasture with the spatial utilisation of the paddock increasing as biomass decreased (Roberts, Trotter, Lamb, Hinch, & Schneider, 2010). This may be associated with the declining biomass resulting in the sheep having to walk further to obtain their required intake. This is further supported in Figure 16 showing an increased level of activity throughout the middle of the day at the end of the trial. Real-time monitoring systems providing information on animal behaviour could make use of this type of data to improve the grazing management of livestock. For example, where the feed value of spilt grain is difficult to determine, detecting a change in time spent grazing could be the trigger point to remove the livestock from the paddock before overgrazing occurs.

This change in grazing pattern is very similar to that subjectively observed experiments with sheep grazing pastures (Trotter, Lamb, Hinch & Guppy, 2010). This study was the first which utilised GNSS collars to collect an objective picture of sheep spatial grazing behaviours on crops. It would be suitable to repeat this experiment across different seasons to observe if the grazing patterns change when greater biomass was available from the start of grazing. Further work is also needed to match animal behaviour with animal speed based on GNSS devices in a crop grazing scenario.

5.3 Relationships between the spatial grazing patterns of sheep grazing crops and soil quality and biomass

The grazing patterns of sheep measured through a livestock residency index showed little correlation with soil quality measurements (EM and Thorium), or NDVI recorded from a UAV. This means that the grazing patterns were unrelated to the soil quality or level of biomass in this experiment. There was a significant variation in biomass between the ungrazed cages at both pre-grazing and post grazing measurement and AGB at harvest, indicating that the variation in soil type across the paddock could result in differences in biomass. Irrespective of this likely variation in biomass, this experiment was unable to demonstrate that sheep on crops have a preferential grazing pattern that is related to biomass or potentially soil quality. However, EM and NDVI were related in some way to LRI as indicated by significant regressions (present irrespective of the very low R^2) but the visual depiction of these relationships did not clearly indicate how they are related. Repeating this trial across multiple years of different seasonal condition may further elucidate these relationships.

Interestingly, there was also little correlation between the grazing or resting LRI's with final grain yield measured from the harvester yield monitor. This may have been due to a very even utilisation of biomass across the paddock given the high stocking rate and limited amount of crop biomass available due to poor early season rainfall. Had there been a more uneven grazing distribution across the paddock resulting in lower crop intake in parts of the paddock, it's possible that changes in plant growth potential and rate of maturity could have been evident, therefore impacting final yield and the relationship with LRI. Further experimental approaches need to incorporate lower stocking rates and grazing pressure when assessing the impact of LRI on yield.

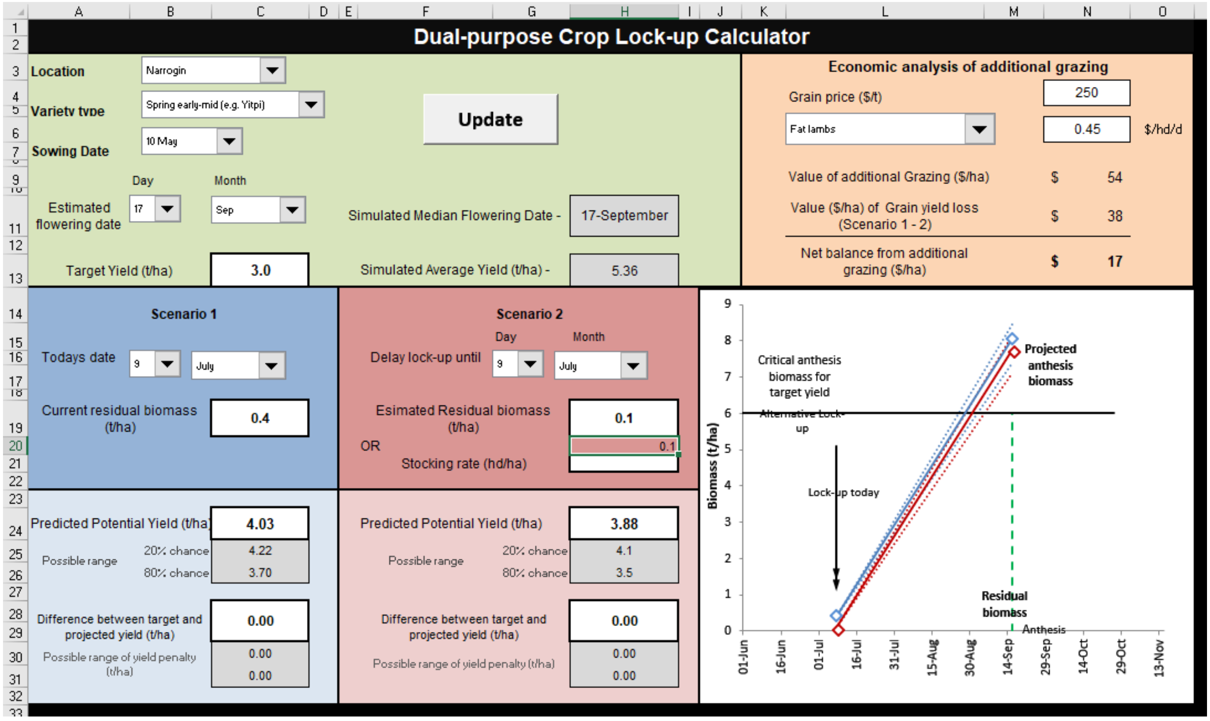
5.4 The accuracy, effectiveness and uses of current sensor technologies to measure crop parameters in a crop grazing system

5.4.1 Predicting biomass using sensor technologies

The decline in biomass during crop grazing needs to be carefully monitored to ensure the crop can recover, regrow and produce grain (Harrison et al., 2011). The difficulty with measuring the change in the biomass of a crop is that the subjective measurement tools commonly and widely used such as rising plate meters, the pasture focussed Lifetime Wool image gallery and other visual assessment methods are more suitable for pastures. An accurate and crop orientated tool is therefore required to monitor the decline in biomass throughout the grazing period in a crop grazing system. This study has demonstrated that certain sensor technologies can detect a change in biomass, and importantly, accurately predict the available biomass (FOO kg DM/ha). Promising results indicate that the Greenseeker can detect small changes in biomass as demonstrated by the sequential biomass cuttings and GS readings. Further, the regression analyses indicated that the Greenseeker was indeed able to accurately predict the available FOO (kg DM/ha) present in the paddock with a R^2 of 0.89 using the pooled data set. An outcome of being able to use a sensor such as the Greenseeker to predict the FOO (kg DM/ha) is that the commonly used subjective biomass measuring techniques are no longer needed or can be used in addition to the more objective and accurate measurements from the Greenseeker. The UAV and satellite based sensors did not result in any significant results in the regression analyses against FOO (kg DM/ha) early in the season, however correlations were evident at higher biomass levels late in the season and are discussed in section 5.4.3.

5.4.2 Combining sensor technology with other tools to assist grazing management

The estimated available FOO (kg DM/ha) derived from the GS NDVI data can be used with tools such as the 'Dual-purpose crop lock-up calculator' developed by CSIRO and DPIRD (Seymour et al., 2015) (Figure 38) to simulate scenarios and give yield estimations and understand the economic impacts of the different grazing strategies. By combining the Greenseeker and the calculator, a producer could get accurate and real-time estimations which they can base their decisions on, whilst spending considerably less time measuring and calculating biomass in the field. For example, in Figure 38 the calculator has utilised the biomass figures recorded on the day that the sheep were removed from the paddock. Scenario 1 (0.4t DM/ha) and scenario 2 (0.1t DM/ha) represent the ungrazed and grazed plots, respectively. These FOO values from the two scenarios resulted in a predicted yield of 4.03t/ha and 3.88t/ha for the ungrazed verses grazed plots using the 'Dual-purpose crop lock-up calculator'. The actual yields for the ungrazed and grazed treatments were 3.82 t/ha and 3.28 t/ha, respectively, showing value in using a predictive tool based on in-season biomass to predict final yield. A specific case example of how the producer could use this calculator in combination with the GS is to evaluate the time point when the sheep need to be removed from the crop before there is a critical decline in yield. It is possible that this tool will allow for an extension to the grazing period on crop and additional livestock benefits without any detriment to the crop.



Dual-purpose Crop Lock-up Calculator

Location: Narrogin
Variety type: Spring early-mid (e.g. Yitpi)
Sowing Date: 10 May
Estimated flowering date: Day 17, Month Sep
Simulated Median Flowering Date - 17-September
Target Yield (t/ha): 3.0
Simulated Average Yield (t/ha) - 5.36

Economic analysis of additional grazing

Grain price ($/t): 250
Fat lambs: 0.45 $/hd/d
Value of additional Grazing ($/ha): $ 54
Value ($/ha) of Grain yield loss (Scenario 1 - 2): $ 38
Net balance from additional grazing ($/ha): **$ 17**

	Scenario 1		**Scenario 2**
Todays date	9 July	Delay lock-up until	9 July
Current residual biomass (t/ha)	0.4	Esimated Residual biomass (t/ha)	0.1
		OR Stocking rate (hd/ha)	0.1
Predicted Potential Yield (t/ha)	4.03	Predicted Potential Yield (t/ha)	3.88
Possible range 20% chance	4.22	Possible range 20% chance	4.1
Possible range 80% chance	3.70	Possible range 80% chance	3.5
Difference between target and projected yield (t/ha)	0.00	Difference between target and projected yield (t/ha)	0.00
Possible range of yield penalty (t/ha)	0.00 0.00	Possible range of yield penalty (t/ha)	0.00 0.00

Figure 38. A screenshot of the user interface of the Excel based Dual-purpose crop lock-up calculator adapted by Philip Barrett-Lennard (agVivo) for this project. Current data shown is from FOO estimations from the GS NDVI data taken at post grazing with scenario 1 being the ungrazed treatment (0.4t DM/ha) and scenario 2 the grazed treatment (0.1t DM/ha).

5.4.3 The use of UAV and satellites to measure changes in biomass

The UAV was utilised in this study to identify the spatial variation in crop biomass across the paddock, highlighting any effect grazing pressure has on crop biomass based on NDVI. Data for the grazed treatment plots at post grazing provided an extremely low NDVI value. The reason for the low NDVI values are not clear, however, given the very low biomass levels, the reflectance values would be a measure of soil reflectance rather than photosynthetically active biomass from the crop. These low NDVI values are expected for the trial soil type as sandy soils, low in organic matter have been shown to result in a low NDVI value (Hill, Donald, Hyder, & Smith, 2004). Additionally, no UAV data was available for dates close enough to the start of grazing which further reduced the ability to investigate the relationship between the UAV and the GS along with the crop biomass. A complete UAV NDVI data set would have been of great benefit to this study especially as a strong correlation ($R^2 = 0.85$) between the Greenseeker and the UAV sensor was observed in in a study investigating the use of these sensors in wheat agronomy and breeding trials (Duan, Chapman, Guo & Zheng, 2017). Similar results were seen in the present trial between UAV NDVI and biomass late in the season prior to flowering ($R^2 = 0.73$).

The Satellite images obtained during the course of the experiment were unable to detect any variation in biomass. Unfortunately, there was no suitable higher resolution imagery (10x10m) Sentinel satellite data obtained close enough to the start of grazing and biomass sampling. Landsat 8 data and also paddock average data from the MODIS Satellite derived from Pastures from Space was provided, however, the Landsat pixels are 30m x 30m and MODIS is 250m x 250m so they are too large to detect variation within and outside the grazing exclusion cages. The shortage of high resolution satellite imagery precludes attempting to establish a formal correlation between datasets in the current study. A recommendation is to consider an additional analysis using potential historical data that could be derived from the newly available daily 4m resolution satellites offered by Planet Labs. At present, this experimental team are unable to obtain these images despite the partnership with Landgate. There are also new commercial services (Farmmap4D, CiBO labs) that have recently become available that are offering biomass predictions (almost) on a real-time- daily basis using 5 day Sentinel satellite data and machine learning techniques to derive accurate algorithms for biomass prediction. A further research program to investigate the potential for the imagery from these satellites to detect change in biomass should be undertaken.

5.4.4 Using sensors to predict the final grain quality at harvest

The UAV F5 NDVI data was a strong predictor of both AGB (t/ha) and grain yield (t/ha) with the respective R^2 values of 0.73 and 0.70. The UAV F5 data was captured when the crop was at GS40 (booting) and GS30 (stem elongation) for the ungrazed and grazed treatments respectively, which was 82 days prior to harvest. Being able to estimate the AGB (t/ha) and grain yield (t/ha) at this stage does not influence any decisions related to the grazing of the crop as that has already occurred. These estimations can however be used to evaluate the output from the CSIRO dual-purpose crop-lock calculator in addition to directing crop management and economic decisions, such as fertiliser applications and forward selling of the grain. Early season measures of crop biomass based on NDVI hold little value in predicting final yield, as shown in

Table 7.

5.4.5 Using sensors to predict nutritive quality

The forage %CP and IVDMD relationships with the sensor technologies was shown to be weak, however, with the addition of FOO (kg DM/ha) as a term improved the regressions but despite being significant they were still moderately weak. For the prediction of forage %CP; the GS reading, FOO (kg DM/ha) and the height could give a producer a rough estimate of the %CP content.

5.4.6 Limitations of the sensor technologies

Several studies have highlighted that at high green biomass levels (greater than 2t GDM/ha) there is a saturation effect on the Greenseeker NDVI readings, which reduces its ability to detect any further changes in biomass beyond the point of saturation (Andersson et al., 2017; Erdle, Mistele & Schmidhalter, 2011). The peak biomass level of 2t GDM/ha was approximately the same level of green biomass observed for the ungrazed treatment (2t GDM/ha @ 19%DM is 0.38t/ha) by the end of grazing. In a crop grazing system this should not be a major limitation for the use of the GS NDVI as crop grazing commences around the green biomass levels of the pre-grazing measurement (± 340 kg fresh/ha) and reduces in biomass over the grazing period. This study also identified that the presence of stubble influenced the GS readings and accuracy. The impact of stubble on the estimation of FOO (kg DM/ha) was higher at the pre-grazing stage (GS13) where FOO estimation could be used alongside anecdotal guidelines (growth stage 13-14) (Kirkegaard et al., 2015; Seymour et al., 2015) to determine the commencement of grazing.

The accuracy of the GS to predict the available FOO (kg DM/ha) reduced as the biomass went below a certain level which follows what was reported by another study where GS readings were sensitive to extra low biomass and ground cover (Erdle et al., 2011). This indicates the Greenseeker prediction accuracy reduced when the biomass was below a certain level. The exact biomass level would be dependent on the row spacing of the crop but in the case of this study it can be suggested that accuracy reduced somewhere between pre-grazing and post grazing green biomass levels which were 390kg GDM/ha and 260kg GDM/ha, respectively.

Height as an additional regression term for FOO (kg DM/ha) increased the strength of the regression when used with the pre-grazing data. However, height was not a significant term in any of the post grazing data set regressions but did perform better in the ungrazed data set compared to the grazed data set. The inclusion of height in the regression for the pre-grazing data set was similarly included in a study by Andersson et al., (2017) using a GS where height was a significant term along with NDVI to predict the biomass.

In addition, several limitations of using the UAV by a producer became evident during the course of the study. The dependency on light would limit the producer to flying the UAV at specific times of the day (Erdle et al., 2011). Additionally, the volume of data produced (Aasen, Burkart, Bolten & Bareth, 2015) and the requirement to process the raw imagery before the NDVI data can be extrapolated would add considerable time to the process as well as the initial training to obtain the skills required. In contrast, the GS is an easy and inexpensive tool to use and derive data from. The value of a UAV in comparison to a Greenseeker is the spatial variability can be measured across the entire paddock provided by the UAV rather than intermittent zones measured by the Greenseeker. This could be valuable given sheep show an uneven grazing distribution and as such some areas of the paddock could be heavily grazed and fall below the critical level earlier, constraining final grain yield. Both NDVI platforms however require calibration with GDM to predict biomass levels with findings suggesting these calibrations need to be independent for the sensing platform used.

Some of the key limitations to the satellite data were demonstrated in section (5.4.3). The possibility of cloud cover or satellites not passing over the property in a timely manner may limit their use for crop grazing management. However, it is possible that the combination of the ‘real-time’ daily biomass calculation derived from 5-day Sentinel satellite data (discussed in section 5.4.3) could be used to create a scout map to direct the producer to key areas of biomass variability to undertake Greenseeker readings. For example, any areas in the paddock that the biomass map identifies as having low biomass levels would be where the producer could then undertake GS NDVI measurements. If these low areas reach a critical level of biomass the producer may then decide to remove the sheep from the paddock. The combination of the two technologies along with biomass-yield prediction tools may be an appropriate tool for assisting with crop grazing management but further research is needed to evaluate these in combination.

5.4.7 Impact of seasonal conditions on the ability to measure biomass using sensors

As mentioned previously, the paddock had been very heavily and evenly grazed, beyond what is commonly recommended (Nicholson et al., 2016). On a more average year the biomass for the ungrazed plots could be around 1t DM/ha compared to the observed 0.4t/ha. Had the grazed plot biomass at the time grazing ceased been higher it is possible that the GS could have accurately predicted this point. Further research needs to be undertaken under different seasonal conditions to fully investigate the potential of the GS to predict the post grazing biomass following improved crop growth rates and levels of biomass.

5.5 Cost benefit analysis

The study has successfully combined the use of GNSS derived livestock grazing maps and harvester yield maps to derive an overall *dual-purpose crop profit map* for the paddock. The *dual-purpose crop profit map* and cost benefit analysis have demonstrated that the reduction in grain income from a lower crop yield due to grazing is more than offset by the income from lamb live weight gain. This produced a 3% higher gross margin for the grazing scenario compared to the ungrazed scenario. If the improvement in ewe liveweight had also been factored in, the gross margin would have been 8% higher. The grain quality improvement is also something that has been observed in other crop grazing trials (Nicholson et al., 2016). It is worth recognising that the seasonal conditions have impacted on the economic results. The early part of the 2017 growing season was particularly difficult with very dry conditions in May and June, which significantly reduced crop and pasture growth. Better growing conditions could have further increased the liveweight gains due to an extended crop grazing time and allowed for better crop recovery from grazing and therefore higher grain yields. This would have made the economics even more favourable for the grazing scenario. Had the grain finishing period been less favourable, the differences in yield between the scenarios may have been higher offsetting any gains from improved livestock performance and grain quality.

The use of GNSS collars to derive a *dual-purpose crop profit map* will be a valuable technique for the future assessment of the benefits of crop grazing. It would be worthwhile repeating this experiment across multiple crop types, seasons and grazing management. Specifically, a *dual-purpose crop profit map* for a prime lamb production system needs to be conducted where crop grazing is compared to pasture/supplementary feeding systems. This comparison will allow for an accurate assessment of the value of the lamb liveweight gain attributable to crop grazing. It is predicted that this comparison will demonstrate that crop grazing increases the value of the lamb carcase, reduces lamb finishing costs and results in a significant higher overall paddock profit compared to the pasture treatment and if the crops were left ungrazed. Another interesting inclusion would be to incorporate stubble grazing into the gross margin calculations and map.

6. Conclusions/recommendations

This study evaluated the role of different sensor technologies to accurately assist with the grazing management of crops. To improve crop grazing management, it is fundamental that technologies and proven protocols be available that better predict crop biomass to assist producers determine when to begin crop grazing and when to remove sheep to minimise the yield penalty. A key finding from this study is that the Greenseeker can accurately predict the available FOO (kg DM/ha) when stubble is removed from the area being measured. The predicted FOO (kg DM/ha) can then be used in conjunction with other calculators and tools that relate biomass to crop yield and economic performance of the farm business. A recommendation for further research is to develop the CSIRO/DPIRD biomass-yield prediction tool (demonstrated in the section 5.4.2) to incorporate biomass values derived from the Greenseeker into an enhanced crop grazing management tool for industry. Alternatively, this tool may support producers to confidently extend the grazing period on crops thus maximising the opportunistic cost benefit of grazing crops. Therefore, the use of this objective calculator and the Greenseeker along with other subjective tools and practices such as exclusion cages to monitor crop growth stage, may give producers greater confidence to graze crops therefore increasing the acceptance and uptake of this management strategy by mixed farmers.

Further studies over multiple seasons and using different crops, with a Greenseeker focussed experimental design could lead to a stronger regression with biomass change and potentially answer additional questions related to the saturation and low biomass thresholds along with methodologies on how to predict the nutritive quality of the crop. The use of UAV's for estimating biomass change due to grazing was shown to be limited in this study given the high utilisation of available biomass by sheep. However, the UAV was a good predictor of grain yield when used later in the season and could be more appropriate for use in crop management decisions. The satellite imagery which was dependent on weather conditions resulted in poor data for critical periods of the study and was not included in the majority of the analysis. However, newer, higher resolution satellites and machine learning algorithms could improve the ability of satellites to predict biomass and be used for crop grazing management in the future. This report identified limitations to the use of the UAV and satellites for estimating biomass which in the short term may be overcome by the versatility of the Greenseeker.

The GNSS collars were able to demonstrate a change in spatial grazing behaviour over the 15-day trial period. However, these patterns were uncorrelated with soil quality measurements taken by geophysical testing (EM and Thorium) and with the NDVI biomass data measurements taken at paddock scale with the UAV over multiple periods. The result occurred despite a variation in biomass across the paddock but it was at below average levels. This trial should be repeated across different (better) seasons to observe if the spatial grazing patterns change when the crop has greater growth potential and higher grazing biomass was available from the start of grazing. A likely benefit of identifying zonal differences in the paddock through spatial grazing linkages with soil quality is the opportunity to use variable rate fertiliser application to improve crop and pasture quality and also targeted soil sampling.

There was also no relationship between the grazing patterns and the final crop yield measured by the harvester. The paddock was very heavily grazed which may have limited the ability to detect a discernible relationship. Had there been uneven grazing due to a lower stocking rate and higher pre-grazing biomass levels in parts of the paddock, along with a better growing potential of the crop due to season, it is possible that changes in plant maturity and therefore impact on final yield may have become evident. Comparison between grazed and ungrazed treatment sites, shows an average yield penalty for grazing of 0.5t/ha. However, this difference is not consistent across all 25 sites, indicating either grazing pressure or soil properties did influence the impact grazing has on final yield. Further experimental approaches to understand the relationship between LRI and yield need to incorporate lower stocking rates and grazing pressure to highlight further effects uneven grazing has on the final grain yield.

This was the first reported study to combine the use of GNSS derived livestock grazing maps and harvester yield maps to derive an overall *dual-purpose crop profit map* for the paddock. The profit map and cost benefit analysis have shown that despite the decline in yield due to crop grazing, the economic benefits due to reduced supplementary feeding and liveweight gains may outweigh the loss of grain income. The use of GNSS collars to derive a *dual-purpose crop profit map* will be a valuable technique for the future assessment of the benefits of crop grazing. A priority should be to develop *dual-purpose crop profit map* for a prime lamb production system where crop grazing is compared to pasture/supplementary feeding systems and to also include the value of stubble grazing.

7. Key messages

The key messages from this project include:

- Producers can potentially use the Greenseeker NDVI tool in conjunction with other tools to predict the change in crop biomass during grazing and determine their crop grazing strategy to minimise yield penalties.
- The spatial grazing patterns of sheep on crops can be evaluated by using GPS tracking collars. These patterns may provide insights into grazing preferences in a paddock.
- The incorporation of spatial grazing maps, yield maps and liveweight data can generate valuable *Dual-purpose gross profit maps* for a paddock.
- Producers should take into account the additional grazing benefits and reduced supplementary feed costs from crop grazing when evaluating the gross margins of a grazed paddock. In this project, with these costs included, crop grazing resulted in comparable gross margins from a paddock despite a potential decline in yield.
- Late season NDVI readings taken using a drone can accurately predict final grain yield and potentially be used to make seasonal management decisions post grazing. However, early season NDVI has a poor relationship with final yield.

8. Bibliography

Aasen, H., Burkart, A., Bolten, A., & Bareth, G. (2015). Generating 3D hyperspectral information with lightweight UAV snapshot cameras for vegetation monitoring: From camera calibration to quality assurance. *ISPRS Journal of Photogrammetry and Remote Sensing*, *108*, 245–259. https://doi.org/10.1016/J.ISPRSJPRS.2015.08.002

Andersson, K., Trotter, M., Robson, A., Schneider, D., Frizell, L., Saint, A., … Blore, C. (2017). Estimating pasture biomass with active optical sensors. *Advances in Animal Biosciences*, *8*(02), 754–757. https://doi.org/10.1017/S2040470017000838

Bell, L. W., Harrison, M. T., & Kirkegaard, J. A. (2015, April 21). Dual-purpose cropping-capitalising on potential grain crop grazing to enhance mixed-farming profitability. *Crop and Pasture Science*, *66*(4), i–iv. https://doi.org/10.1071/CPv66n4-FO

Bell, L. W., Moore, A. D., & Kirkegaard, J. A. (2014). Evolution in crop-livestock integration systems that improve farm productivity and environmental performance in Australia. *European Journal of Agronomy*, *57*, 10–20. https://doi.org/10.1016/j.eja.2013.04.007

Campbell, N., & Arnold, G. (1973). The visual assessment of pasture yield. *Australian Journal of Experimental Agriculture*, *13*(62), 236–267.

CSIRO and Bureau of Meteorology. (2015). *Projections: Atmosphere and the land*. *Climate Change in Australia Information for Australia's Natural Resource Management Regions: Technical Report*. Retrieved from https://www.climatechangeinaustralia.gov.au/media/ccia/2.1.6/cms_page_media/168/CCIA_2015_NRM_TechnicalReport_WEB.pdf

Dove, H., & Kirkegaard, J. (2014). Using dual-purpose crops in sheep-grazing systems. *Journal of the Science of Food and Agriculture*, *94*(7), 1276–1283. https://doi.org/10.1002/jsfa.6527

Duan, T., Chapman, S. C., Guo, Y., & Zheng, B. (2017). Dynamic monitoring of NDVI in wheat agronomy and breeding trials using an unmanned aerial vehicle. *Field Crops Research*, *210*, 71–80. https://doi.org/10.1016/j.fcr.2017.05.025

Erdle, K., Mistele, B., & Schmidhalter, U. (2011). Comparison of active and passive spectral sensors in discriminating biomass parameters and nitrogen status in wheat cultivars. *Field Crops Research*, *124*(1), 74–84. https://doi.org/10.1016/j.fcr.2011.06.007

Frischke, A. J., Hunt, J. R., McMillan, D. K., & Browne, C. J. (2015). Forage and grain yield of grazed or defoliated spring and winter cereals in a winter-dominant, low-rainfall environment. *Crop and Pasture Science*, *66*(4), 308. https://doi.org/10.1071/CP14273

Harmoney, K. R., Moore, K. J., George, J. R., Brummer, E. C., & Russell, J. R. (1997). Determination of Pasture Biomass Using Four Indirect Methods. *Agronomy Journal*, *89*(4), 665. https://doi.org/10.2134/agronj1997.00021962008900040020x

Harrison, M. T., Evans, J. R., Dove, H., & Moore, A. D. (2011). Dual-purpose cereals: can the relative influences of management and environment on crop recovery and grain yield be dissected? *Crop and Pasture Science*, *62*(11), 930. https://doi.org/10.1071/CP11066

Harrison, M. T., Evans, J. R., & Moore, A. D. (2012). Using a mathematical framework to examine physiological changes in winter wheat after livestock grazing: 2. Model validation and effects of grazing management. *Field Crops Research*, *136*, 127–137. https://doi.org/10.1016/J.FCR.2012.06.014

Hill, M. J., Donald, G. E., Hyder, M. W., & Smith, R. C. G. (2004). Estimation of pasture growth rate in the south west of Western Australia from AVHRR NDVI and climate data. *Remote Sensing of Environment*, *93*(4), 528–545. https://doi.org/10.1016/j.rse.2004.08.006

Hyder, M., & Curnow, M. (2016). *Supplementary feeding and feed budgeting of sheep*. Retrieved from https://www.agric.wa.gov.au/feeding-nutrition/supplementary-feeding-and-feed-budgeting-sheep?page=0%2C4#smartpaging_toc_p4_s3_h3

Kelman WM, & H., D. (2009). Growth and phenology of winter wheat and oats in a dual-purpose management system. *Crop and Pasture Science*, *60*(10), 921–932.

Kingwell, R., Anderton, L., Islam, N., Xayavong, V., Wardell-Johnson, A., Feldman, D., & Speijers, J. (2014). Broadacre farmers adapting to a changing climate. In *Applied Studies in Climate Adaptation* (pp. 130–138). https://doi.org/10.1002/9781118845028.ch15

Kingwell, R., & Pannell, D. J. (2005). Economic trends and drivers affecting the grainbelt of Western Australia to 2030. *Australian Journal of Agricultural Research*, *56*(6), 553–561. https://doi.org/10.1071/AR04196

Kirkegaard, J. (2013). *Optimising the integration of dual-purpose crops in the high-rainfall zone. Project CSP00132,*.

Kirkegaard, J. A., Lilley, J. M., Hunt, J. R., Sprague, S. J., Ytting, N. K., Rasmussen, I. S., & Graham, J. M. (2015). Effect of defoliation by grazing or shoot removal on the root growth of field-grown wheat (Triticum aestivum L.). *Crop and Pasture Science*, *66*(4), 249–259. https://doi.org/10.1071/CP14241

Li, F., Miao, Y., Zhang, F., Cui, Z., Li, R., Chen, X., … Jia, L. (2009). In-Season Optical Sensing Improves Nitrogen-Use Efficiency for Winter Wheat. *Soil Science Society of America Journal*, *73*(5), 1566. https://doi.org/10.2136/sssaj2008.0150

Mata, G., Henry, D. A., Gherardi, S. G., & Smith, R. C. G. (2004). PASTURES FROM SPACE – INTRODUCTION TO THE TECHNOLOGY ON FARM. *Animal Production in Australia Anim. Prod. Aust. Anim. Prod. Aust. Anim. Prod. Aust. Anim. Prod. Aust. Anim. Prod. Aust*, *25*(25), 281–112. Retrieved from http://www.publish.csiro.au/sa/pdf/SA0401126

Miller, D. R., Dean, G. J., & Ball, P. D. (2010). Influence of end-grazing forage residual and grazing management on lamb growth performance and crop yield from irrigated dual-purpose winter wheat. *Animal Production Science*, *50*(6), 508. https://doi.org/10.1071/AN09163

Nicholson, C., Frischke, A., & Barrett-Lennard, P. (2016). *GRAZING CROPPED LAND*. Retrieved from http://www.grainandgraze3.com.au/resources/Grazing_Cropped_Land_June_2016_.pdf

Putfarken, D., Dengler, J., Lehmann, S., & Hardtle, W. (2008). Site use of grazing cattle and sheep in a large- scale pasture landscape: a GPS/GIS assessment. *Appl. Anim. Behav. Sci.*, *111*, 54–56.

Roberts, J., Trotter, M., Lamb, D., Hinch, Ge., & Schneider, D. (2010). Spatio-temporal movement of livestock in relation to decreasing pasture biomass.

Rutter, S. M. (2010). Review: Grazing preferences in sheep and cattle: Implications for production, the environment and animal welfare. *Canadian Journal of Animal Science*, *90*(3), 285–293. https://doi.org/10.4141/CJAS09119

Seymour, M., England, J. H., Malik, R., Rogers, D., Sutherland, A., & Randell, A. (2015). Effect of timing and height of defoliation on the grain yield of barley, wheat, oats and canola in Western Australia. *Crop and Pasture Science*, *66*(4), 287. https://doi.org/10.1071/CP13411

Trotter, M. G., Lamb, D. W., Hinch, G. N., & Guppy, C. N. (2010). Global navigation satellite system livestock tracking: system development and data interpretation. *Animal Production Science*, *50*(6), 616. https://doi.org/10.1071/AN09203

Virgona, J. M., Gummer, F. A. J., & Angus, J. F. (2006). Effects of grazing on wheat growth, yield, development, water use, and nitrogen use. *Australian Journal of Agricultural Research*, *57*(12), 1307. https://doi.org/10.1071/AR06085

Zadocks, J. C., Chang, T. T., & Konzak, C. F. (1974). A decimal code for the growth stages of cereals. *Weed Research*, *14*(6), 415–421. https://doi.org/10.1111/j.1365-3180.1974.tb01084.x

9. Appendix

9.1 Imagery

Figure 39. Trial paddock NDVI values derived from PfS

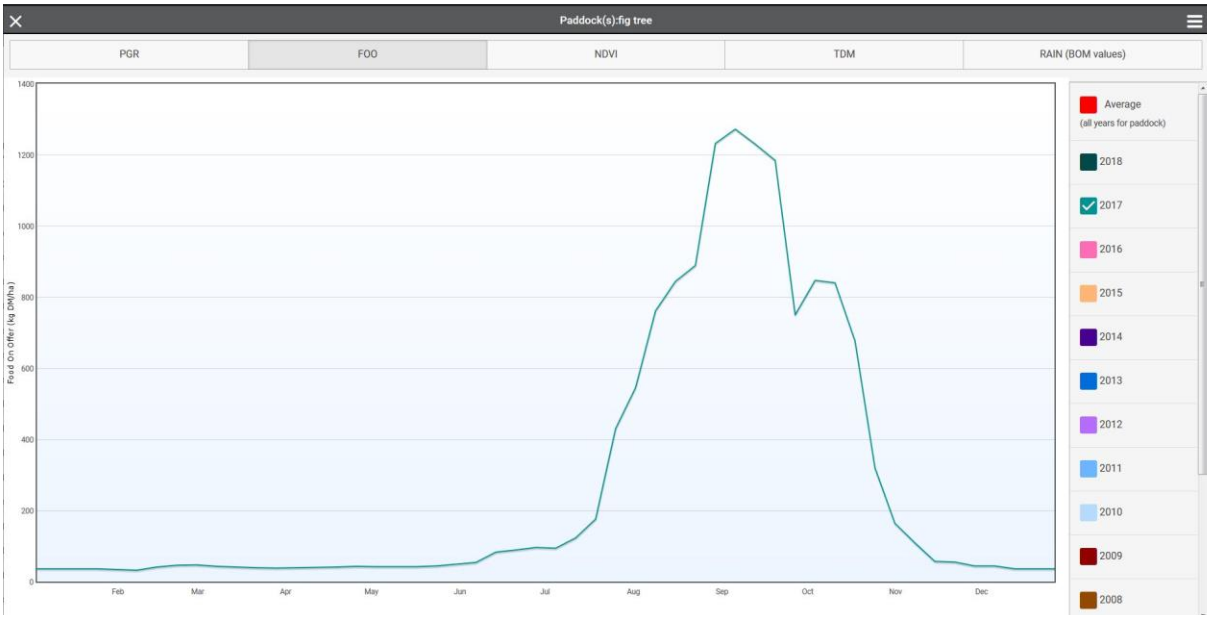


Figure 40. Trial paddock FOO derived from PfS.