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Prepared by: Karl Andersson
University of New England

with contribution from
Mark Trotter, Derek Schneider, Andrew Robson, David Lamb University of New England

Acknowledgements: Lewis Kahn, Matthew Monk, Luke Gleeson, Kathryn Conroy, Jim Shovelton, Ian Gamble, Peter Schroeder, Chris Blore, Tony Butler, Alana Starkie, Brad Wooldridge, and all the participants in the Participatory Research Groups

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Biomass business II – Tools for real time biomass estimation in pastures

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Abstract

The Biomass Business II (BB2) project evaluated the potential for active optical sensors (AOS) to provide reliable estimates of pasture biomass. The project was focussed in the high rainfall zone of south–eastern Australia and aimed to develop calibrations for AOS and provide a data management package that can be easily used by producers. The project was part of the Grazing Systems Management Pillar of MLAs Feedbase Investment Plan and was supported by MLAs Participatory Research Groups (PRG).

Six pasture types were assessed – tall fescue, phalaris, perennial ryegrass, white clover, lucerne and cocksfoot. Data collection involved measuring normalised difference vegetation index (NDVI), pasture height, taking cuts to ground level, sorting into green, senescent and clover, and measuring the dry weights. Green dry matter was regressed against NDVI and height for each campaign, and again for pooled data regional data. The most commonly suitable models were simply the NDVI, height, or a combined NDVI x height index. The calibrations are available to graziers through the Biomass mobile device application. The objective feed estimates provided through the Biomass app can allow pasture growth to be monitored and support stock management decision making.

Executive summary

Accurate and objective measurement of pasture biomass is a key avenue whereby producers can better meet the feed requirements of their livestock. Accurate, real-time biomass estimates also enable producers to meet residual pasture targets and the subsequent rate of pasture regrowth along with overall productivity. It has been estimated that improved grazing management decisions based on accurate estimates of pasture biomass has the potential to increase farm profitability by approximately 10% in Australian beef and sheep enterprises.

The Biomass Business II (BB2) project ran from August 2013 to August 2017 and was co-funded by MLA and the Co-operative Research Centre for Spatial Information to evaluate the potential for active optical sensors (AOS) to estimate pasture biomass in the high rainfall zone of south–eastern Australia. The project was initiated following recommendations from an MLA review of the potential for information technologies to improve decision making for the southern livestock industries (B.GSM.0004). Of the review's recommendations, this project aimed to improve feed allocation and the ability of graziers to understand, manage and optimise pasture production. The outcome of this evaluation of the AOS technologies was contribute to increasing the average of efficient allocation of feed from 40% to 60% of optimum levels. Compared to other technologies available, the benefits of the AOS were seen as cost, and ability to discern the green component.

This project aimed to develop calibrations for AOS and provide a data management package that can be easily used by producers. The core research area was at the University of New England, Armidale NSW, with principal satellite sites in Kingstown (Northern slopes, NSW), Guyra and Walcha (New England Tablelands, NSW), Hamilton, Rokewood, Shelford and Mansfield (Victoria), and Launceston (Midlands, Tasmania). Additional data was collected at Forbes (central west NSW) and Arthur River (Western Australia). Data collection remote from Armidale was taken by local groups supported by MLAs Participatory Research Groups (PRG).

Six pasture types were assessed – tall fescue, phalaris, perennial ryegrass, white clover, lucerne and cocksfoot. The sites were selected with input from the PRGs, and were commonly mixed swards. Data collection involved measuring normalised difference vegetation index (NDVI), pasture height, taking cuts to ground level, sorting into green, senescent and clover, and measuring the dry weights. Photos were taken of the samples before and after the pasture was cut. Eight to 15 samples were generally taken in each set of cuts (a campaign). Total and green dry matter were then calculated and regressed against NDVI and height for each campaign. At the principal satellite sites, campaigns were conducted three times per year over three years (early, mid and late growing season), with a fourth campaign at the Armidale and Tasmania sites. More ad-hoc data was collected at Forbes and Arthur River. In all, 1969 samples over 210 campaigns were analysed.

The project has provided a proof-of-concept that AOS can be used to help provide objective estimates of green pasture biomass. In many campaigns, the NDVI 'saturates' as the scanned canopy prevents detection of much of the GDM below the canopy. Another limitation was identified on the fertile pastures across the Victorian sample sites, where low NDVI readings were not obtained due to very green pastures and dark soil. This high baseline made for only a narrow range in NDVI and placed most of the readings close to or into the saturation zone. This NDVI saturation necessitates the inclusion of height in many of the calibration models. For each campaign, the best fit calibrations

varied in using NDVI, height, a combined index, or various transformations of the input data. However, the most commonly suitable models were NDVI, height, a combined NDVI x height index and NDVI x log(height).

Eighty-two percent of campaigns had strong relationships ($r^2 > 0.70$) between GDM and the input data. Data was then pooled to develop regional, seasonal and species specific calibrations. Calibrations with $r^2 > 0.7$ were loaded into a mobile device application ('app') developed by the project to deliver GDM estimates in real time. Graziers can enter the required NDVI or height measurements taken in their paddocks to obtain feed estimates to support their management decisions. The calibrations are provided for: the temperate grasses, lucerne and white clover on the northern tablelands, NSW; tall fescue and lucerne on the northern slopes, NSW; phalaris and perennial ryegrass in north central and south western Victoria, perennial ryegrass and white clover in the Midlands in Tasmania. In addition, indicative or custom calibrations based on smaller sample numbers are provided for mixed pastures in central west NSW, and perennial ryegrass and clover in Arthur River, WA.

In order to further support the red meat industry, several avenues for future work are recommended. These include: maintaining and improving the MDA, including crowd-sourced data; investigate engineering solutions for height measurement; incorporate/calibrate remotely sensed data; and investigate linkages with planner pasture quality, fodder budgeting, stocking rate calculator, and paddock rotation.

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1 Background

1.1 Purpose of the research

Accurate and objective measurement of pasture biomass is a key requirement for producers for improving grazing system productivity, allowing graziers to better meet the feed requirements of their livestock. Accurate, real-time biomass estimates also enable producers to meet residual pasture targets, resulting in increased pasture utilisation, subsequently increasing pasture growth rates along with overall productivity (Zhao *et al.* 2007; Westwood 2008). Henry *et al.* (2012) estimate that improved grazing management decisions based on accurate estimates of pasture biomass has the potential to increase farm profitability by approximately 10% in Australian beef and sheep enterprises.

In a review of the potential for information technologies to improve decision making for the southern livestock industries commissioned by Meat and Livestock Australia (MLA) (B.GSM.0004 — Potential), Henry *et al.* (2012) identified the following as significant opportunities for producers in using information technologies:

1. Improved pasture production through soil fertility assessments and variable rate fertiliser application
2. Improved feed allocation — allocating appropriate quality and quantity of feed to different classes of stock in a timely manner
3. Pasture yield mapping — understanding, managing and optimising pasture production within and between paddocks
4. Feed prediction - the mitigation of risks associated with adverse climatic conditions and opportunities associated with good seasons

This project addresses the second and third opportunities through the development of tools for real time estimation of biomass and allocation of pasture resources to meet feed supply demands. Extension tools such as Prograze highlight the opportunity for farmers to assess pasture biomass and allocate stock to paddocks on the basis of matching feed demand and feed supply. However, the determination of feed availability using the techniques provided through Prograze and other methods can be subjective and time consuming, and still and subject to error. Producers can find it difficult to get accurate estimates of pasture biomass. While some producers have well developed skills in terms of visualizing accurate biomass estimates and can do this across a number of different seasonal conditions it is not a universal skill (Edwards *et al.* 2011). Even where absolute estimates may be inaccurate, producers can still adequately use their own relative estimates to make appropriate management decisions. However, the differences in experience and the challenges that exist in obtaining objective data from across the industry means that some producers are likely to benefit from more objective measurements. Indeed, it has been estimated that producers are on average achieving 40% of the optimum level in terms of efficient allocation of feed and that precision technologies can increase this to 60%. Economic analysis indicates that an improvement in feed allocation will result in an increase in gross margin / ha (gm/ha) of $96 for sheep and $52 for cattle enterprises (Henry *et al.* 2012).

While tools to accurately measure pasture biomass exist (e.g. C-DAX or sonar pasture meter) within the grazing sector, they are expensive (i.e. greater than $5000 in cost), require significant regional calibration and/or struggle to delineate the green fraction (most important for predicting animal performance on pasture). The challenge has been to develop a technology which is low cost and is also capable of being deployed from a vehicle and can combine readings with GPS technology to build a pasture biomass map.

Newer technologies such as Active Optical Sensors (AOS) have been developed for use in the cropping industry, ostensibly for inferring crop nitrogen levels. These handheld devices direct a beam of light onto the canopy and an on-board detector records the returning radiation and calculates the optical reflectance of the target canopy in those specific wavelengths. The AOS are neither dependent nor influenced by ambient light, in contrast to a passive sensor. They are relatively low cost, can be deployed from a vehicle and have the potential to be integrated with GPS to provide spatial measures of biomass. Research has shown that AOS have the potential to provide estimates of green pasture biomass that compare favourably with other non-destructive techniques (Teal *et al.* 2006; Freeman *et al.* 2007; Trotter *et al.* 2010; Cabrera-Bosquet *et al.* 2011; Shaver *et al.* 2011).

Challenges remain in making this AOS technology commercially available. This includes the need to develop a calibration and data management package that can be easily used by producers. This BB2 project, co-funded by MLA and Co-operative Research Centre for Spatial Information (CRCSI), addresses that need. The project will assess the potential for AOS to provide to objective estimates of pasture biomass. Calibrations of reliable estimates will be created and provided in real-time through a mobile device application (MDA).

2 Project objectives

2.1 Key research objectives

2.1.1 Evaluate the potential for Active Optical Sensors (AOS) to measure pasture biomass in the high rainfall zone of south-eastern Australia.

The sensors currently available for use in Australia have been developed for use in the cropping industry. To evaluate their potential for these sensors to estimate biomass in real time, a series of calibrations and measurements will be required to fully evaluate their potential. Following this stage, protocols for the use of the sensors and their relationship with biophysical measurements will be developed.

This will occur across a range of species, environments and seasons and will occur for two devices which are commercially available for crop production — the Trimble Greenseeker Handheld and the Crop Circle ACS210.

This key research objective is addressed in Section 3 (Methodology).

2.1.2 Develop a series of regional, seasonal and species specific calibrations that can be used by graziers to measure biomass using AOS for six key pastures types: ryegrass, fescue, phalaris, sub-clover, cocksfoot and lucerne.

Across seasons, locations, species and with a range of legume:grass mixes, the AOS device will be calibrated to measure biomass. This will develop both generic calibration equations and techniques for the "self-generation" of calibration equations for the measurement of pasture biomass.

This key research objective is addressed in Section 4.2.

2.1.3 Develop a Mobile Device Application (MDA) supporting the use of AOS as a real-time biomass estimation tool integrating the regional, seasonal and species calibrations and incorporating a simple self-calibration process to allow red meat producers to develop their own location specific calibrations.

The MDA will convert the AOS output into a value which estimates biomass. There will be a centralised web-based server for updates where data will be stored. The MDA will be designed to search the server for updates to calibrations authorised by the research team.

The MDA will enable multi-point self-calibration. This refers to the process of fitting a calibration curve as a result of the collection of multiple individual AOS measurements which are accompanied by corresponding, physical, biomass measurements.

Self-calibration will occur as a result of data collection (physical and AOS), uploading to a web-based server where statistical analysis will occur to calculate calibration curves for the specific situation. These user generated calibrations will then be made available within their library of calibrations within their MDA.

The data generated by producers through the self-calibration process will enable crowd sourcing of AOS sensor to biomass calibrations which will be used to extend the library of available species/season and region calibrations. This user generated data will need to be independently assessed before integration as a calibration available to the wider community.

As part of the commercialisation plan to be developed, the MDA will be developed and tested by end users, including farmers, farmer groups and their advisors. This will identify the system requirements for the MDA development. Where possible, there will be integration with other relevant MLA-funded projects.

Training packages and programs will be developed and delivered to producers and their advisors.

This key research objective is addressed in Section 4.7.

2.2 Additional objectives

2.2.1 Train one PhD student and one post-doctoral fellow.

A PhD student will be recruited to evaluate the potential for integration of digital image analysis from the MDA with AOS systems to provide refined measures of biomass in mixed species swards. The post-doctoral research fellow will undertake the field work and determine the methodology to calibrate the AOS.

This objective is addressed in Section 4.8.

2.2.2 Pillar meetings and membership — Feedbase Investment Plan.

Involvement in pillar membership of the Feedbase Investment Plan This project sits within the Grazing Systems Management Pillar of the Feedbase Investment Plan (FIP). Each pillar has a Pillar Advisory Committee whose role is to coordinate and integrate project activity within each pillar. Membership of the pillar advisory committee includes all project leaders within the relevant pillar. It is expected that the Project Leader will attend pillar meetings 1-2 times per year where this project will be discussed.

This objective is addressed in Section 4.9.

2.2.3 Participatory R&D

The project will work with MLAs Participatory R&D program to provide farmers with the opportunity to "test" the research in a range of environments. The work requirement will be negotiated between MLA and the project team.

This objective is addressed in Section 4.10.

3 Methodology

3.1 Data collection

3.1.1 Site description

Sets of measurements and pasture cuts (campaigns) were taken at a range of sites around Australia across several seasons over three years to evaluate, calibrate and validate AOS for measuring pasture biomass. The main areas of interest were in the high rainfall zone of south eastern Australia. Several additional sites were also included. The core research hub was in Armidale, NSW with satellite sites at Walcha, Guyra and Gostwyck in northern NSW representing the New England Tablelands (NET), Kingstown in northern NSW representing the norther slopes, sites throughout Victoria (Hamilton, Killeen, Mansfield, Moutajup, Rokewood, Shelford, Casterton, Coleraine, Woorndoo), and the midlands in Tasmania (near Bishopsbourne, Cressy and Westwood). Additional sites included Forbes in central-western NSW, and Arthur River-Katanning in Western Australia (

Figure 3-1). Sampling at the main sites were taken at least three times a year (early, mid and late season) over three years, with a more ad-hoc approach at the additional locations. Sampling at the satellite sites was conducted in collaboration with MLAs participatory research groups who also assisted with selecting the paddocks to be sampled.

The pastures sampled included tall fescue (*Festuca arundinacea*), perennial ryegrass (*Lolium perenne*), phalaris (*Phalaris aquatica*), lucerne (*Medicago sativa*), white clover (*Trifolium repens*) and mixed-sward pastures also containing cocksfoot (*Dactylis glomerata*) and native grasses with variable amounts of clovers. At the core research hub, sown, relatively homogenous swards or tall fescue, ryegrass, phalaris, lucerne and white clover were sampled, though over time the proportion of other species increased. Phalaris, tall fescue and perennial ryegrass were also sampled in established pastures on the UNE farms at Armidale. The other NET sites were fescue, cocksfoot and mixed sward pastures. Lucerne and tall fescue pastures were sampled at Kingstown, while the pastures at Forbes were mixed native or introduced swards. The sites in Victoria were dominantly perennial ryegrass or phalaris, with a variable clover component. In Tasmania, three sites were perennial ryegrass, with white clover at a fourth. The predominant species sampled at Arthur River were perennial ryegrass and clovers.

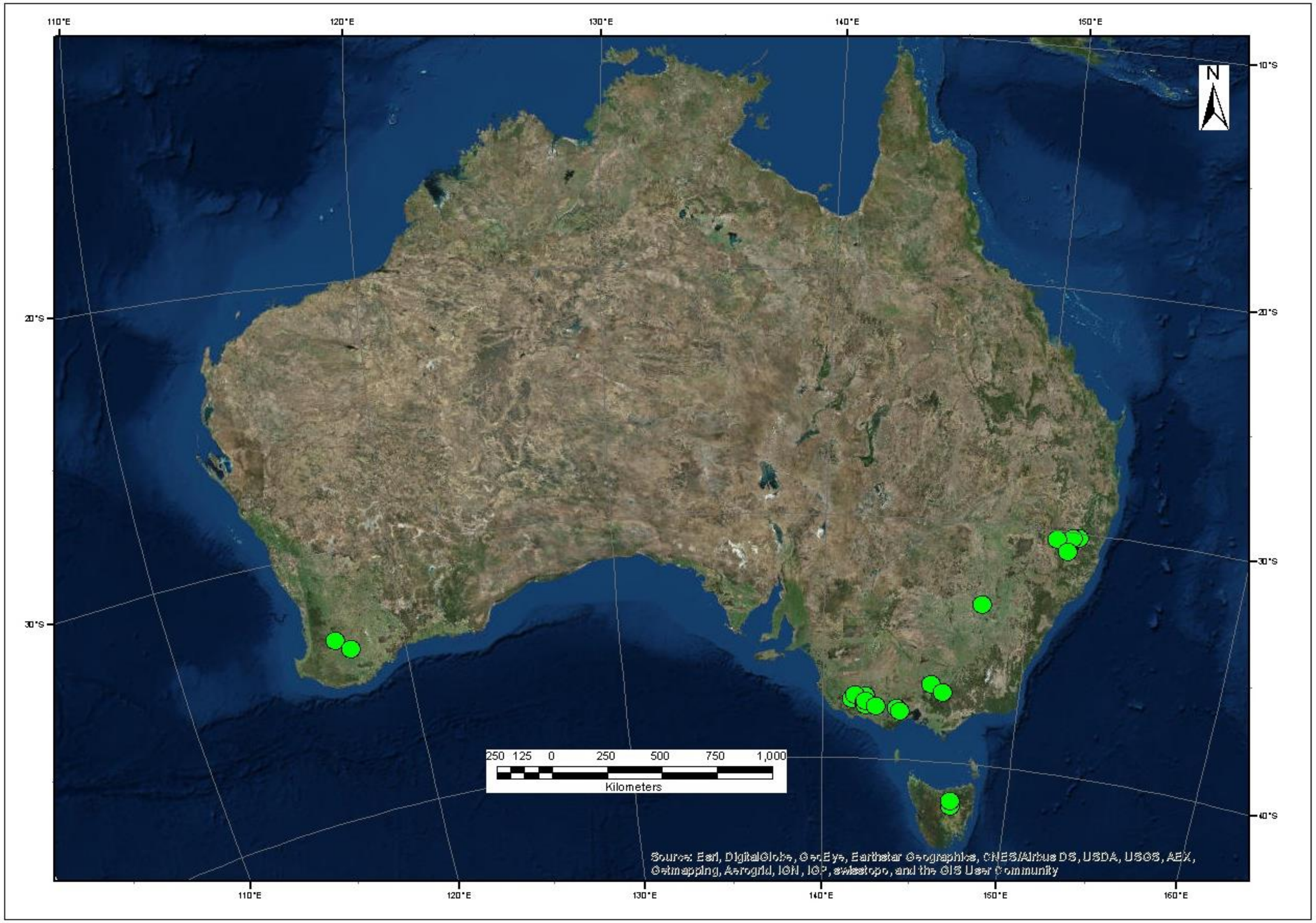

Figure 3-1. Locations for pasture measurements.

3.1.2 Sampling protocol

We collected data from between 8 and 15 samples per site, obtaining a range in pasture biomass, pasture height, and the normalised difference vegetation index (NDVI, Equation 1) values. Each set of cuts at a site represented a campaign. Before cutting the pasture, we measured the reflectance with two AOS – the Holland Scientific Crop Circle and the Trimble GreenSeeker. The AOS were mounted at 1 m on a frame to centre the AOS footprint over the sampling area, and the NDVI value was determined from the average of 100 measurements. The pasture height was then measured using a falling plate (Rayburn and Lozier 2003). The falling plate provides a 'bulk height', improving the correlation of height with pasture biomass (Michalk and Herbert 1977; Rayburn and Lozier 2003). We then cut pasture in a 70 cm x 30 cm quadrat, a size to suit the slightly different footprints of the two AOS devices. Post-cut reflectance was recorded by AOS, and photos were taken before and after cutting for quality control. The pasture samples were collected in paper bags, and stored in a cool room unless sorted on the same day. Following analysis of the first years' data showing no consistent benefit using both AOS, use of the Crop Circle by the PRGs was generally discontinued, and NDVI was recorded with the GreenSeeker only (see Section 4.5 for details).

$$NDVI = \frac{\mathrm{NIR-Red}}{\mathrm{NIR+Red}} \qquad \text{(Equation 1)}$$

where NIR and Red are the proportions of near-infra red and red light, respectively, of incident light reflected to the detector.

In the laboratory, the mass of the samples was recorded, then a subsample (at least 30 g) was to be sorted into green and senescent material. The subsamples and remaining samples were then oven dried for 48 hours at 70^{o}C or until a stable mass was achieved, and dry weights were recorded. The GDM and total dry matter (TDM) per hectare were then calculated by the ratio of the quadrat to a hectare. The groups collecting the cuts were trained to ensure consistent data quality, however samples that were not adequately cut (assessed from the site photos) were excluded from further analysis. Reasons for excluding samples included factors such as: problems encountered in sampling due to wet ground which resulted in substantial pasture being smeared into the mud preventing collection, incomplete cuts (not cut to ground), and suspicion of soil particles being included in the weighed pasture samples. This last factor was initially identified by high pasture biomass per cm (above 600 kg total dry matter per centimetre) and discussed with participatory groups.

Data analysis and modelling were performed in MS Excel (2013) and R (R Development Core Team 2017). As results were received, campaigns for regional groups were combined according to season, proximity and pasture type. From these datasets, GDM and TDM were fitted against NDVI, height and transformed data, and a combined NDVI x height index, as well as log transformations of these inputs. Calibrations for GDM and TDM for individual campaign and pooled data were developed from these fits. Descriptive statistics of the calibrations, including mean, standard deviation (SD), root-mean-squared error (RMSE, Equation 2), coefficient of variation (CV, Equation 3), and range, were determined for each campaign:

$$RMSE = \sqrt{\frac{\sum_1^n (y_p - y_m)^2}{n}} \qquad \text{(Equation 2)}$$

where y_p is the predicted and y_m is the measured GDM, respectively and n is the number of samples.

$$CV = \frac{RMSE}{\bar{y}} x\ 100 \qquad \text{(Equation 3)}$$

where $\bar{y}$ is the mean GDM.

A model was rated excellent, good, acceptable or poor if the CV% were <10%, 10–20%, 20–30% or >30%, respectively (Jamieson *et al.* 1991).

3.1.3 Pasture quality

During the last sampling period, a set of samples from a phalaris-based pasture near Hamilton were targeted for quality testing. Single samples were collected monthly. The samples were cut half-way down, then to ground and sorted into green and senescent components as above. Twenty seven samples were crushed, dried and stored for pasture quality testing by NIR analysis at FeedTest in Werribee, Victoria. Six samples were identified by the laboratory as outliers, and wet chemistry was performed on these six samples for verification of results. The analyses included crude protein (CP), acid detergent fibre (ADF), neutral detergent fibre (NDF), digestibility (DOMD), water soluble carbohydrates, fat, and ash (all as % of dry matter), and estimated metabolisable energy (ME; MJ/kg DM; calculated as (0.203 x DOMD%) - 3.001). The quality results were compared for the upper and lower, and green and senescent, portions of the pasture over 5 months. The weighted average of each test result was regressed against the NDVI from the GreenSeeker.

4 Results

4.1 Overall data

4.1.1 Data quality

Overall, 3187 samples were collected during the project. After data verification, 1969 samples were included for analysis. The reasons for data being exclude included incomplete cutting of the pasture in the quadrat, the pasture composition not being representative of the target species (generally due to weed encroachment), 'hot-spotting' of the AOS (e.g. where an unevenly distributed plants in the quadrat caused a biased reading), dry stalks supporting the plate causing an unrepresentative height, not enough pasture sampled for a reliable measure (e.g. less than 50 kg GDM/ha), transcription errors, or likely inclusion of soil in the sample. This amount of culled data resulted from difficulty in sampling conditions encountered throughout the project and some lack of adherence to protocols. The collection of photos at each sample did however support the inclusion or exclusion of data, resulting in a robust database for analysis.

4.1.2 Pasture biomass calibrations

There was a general trend of increasing GDM with NDVI and height, however the relationships were too broad to be meaningful (

Figure 4-1). The majority of pasture samples were less than 5 000 kg/ha, and up to 20 cm in height. The majority of NDVI values ranged between 0.2 and 0.9.

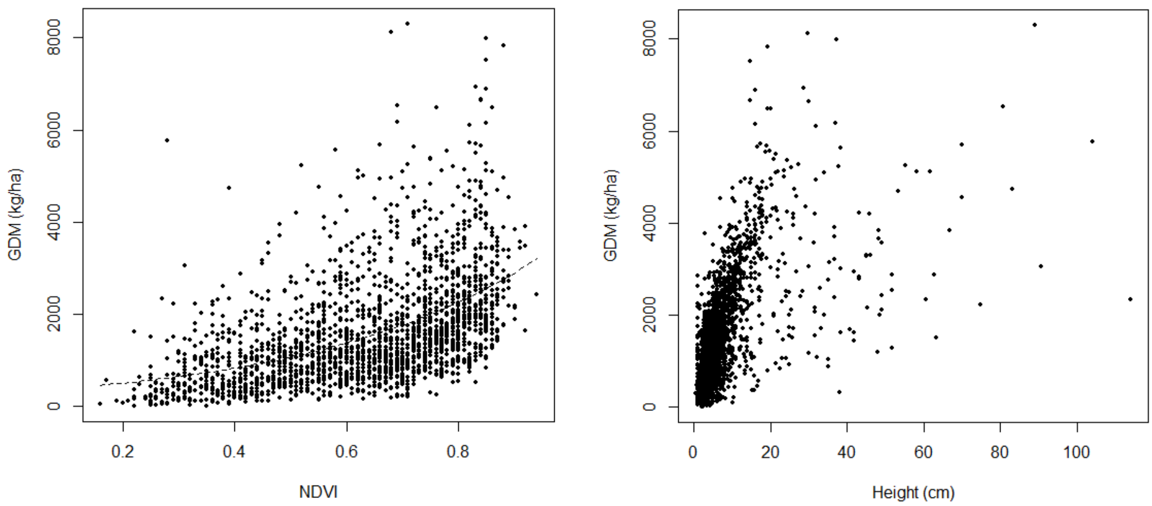

Figure 4-1. GDM (kg/ha) v NDVI and height for all the included sample data.

To explore the usefulness of the AOS and height in estimating pasture biomass, the GDM was regressed against NDVI, height, the NDVI x height index, and transformations of these inputs for each campaign. Of the 211 campaigns with at least 5 samples, all bar eight had at least one statistically significant model fitted ($p<0.05$), and for these more than 82% of had r^2 greater than 0.7 (

Figure 4-2). The r^2 indicates that proportion of variation in GDM that is explained by the measured height, NDVI, or their combination. The campaigns that could not be modelled generally had insufficient range in the NDVI (<0.2 units), height (<5 cm) or GDM (<1000 kg/ha). The data from these individual campaigns could, however, be used for the pooled calibrations (section 4.3**Error! Reference source not found.**).

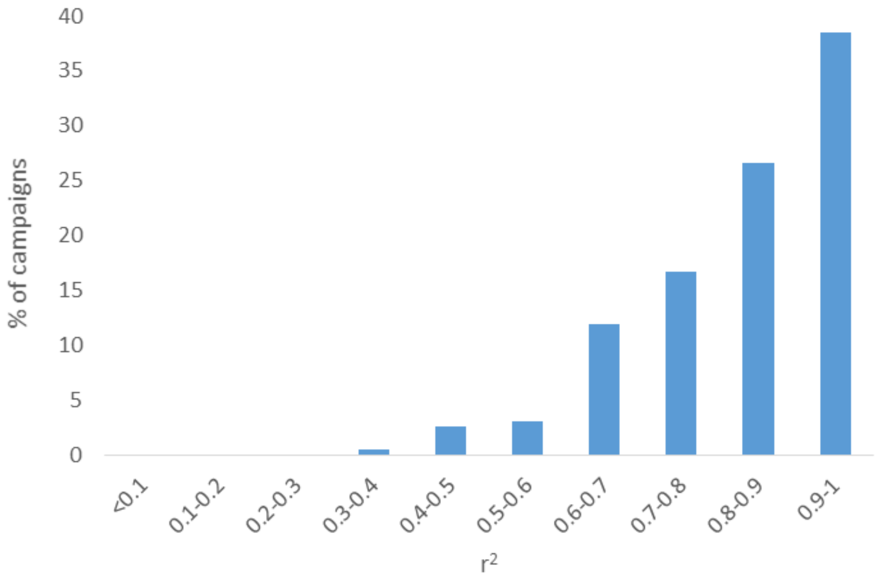

Figure 4-2. Percentage of campaigns containing at least 5 samples in each decile of r^2 for the best fitted model.

Typically, the relationship between GDM and NDVI follows an exponential curve (

Figure 4-3a). A consequence of this pattern is a 'saturation' with the GDM increasing steeply for only a limited increase in NDVI values, with obvious lack of model sensitivity at higher NDVI values. This saturation occurs as the scanned canopy prevents detection of the GDM below the top few leaves (Liu *et al.* 2012; Schaefer and Lamb 2016). The relationship between biomass and NDVI breaks down above a leaf area index of 3 (Weiser *et al.* 1986; Serrano *et al.* 2000). Pasture height is also commonly related to GDM (King *et al.* 1986) (

Figure 4-3b). The inclusion of height with NDVI, as an NDVI x height index, has been used to overcome some of the limitations of NDVI saturation (Freeman *et al.* 2007; Schaefer and Lamb 2016) (

Figure 4-3c).

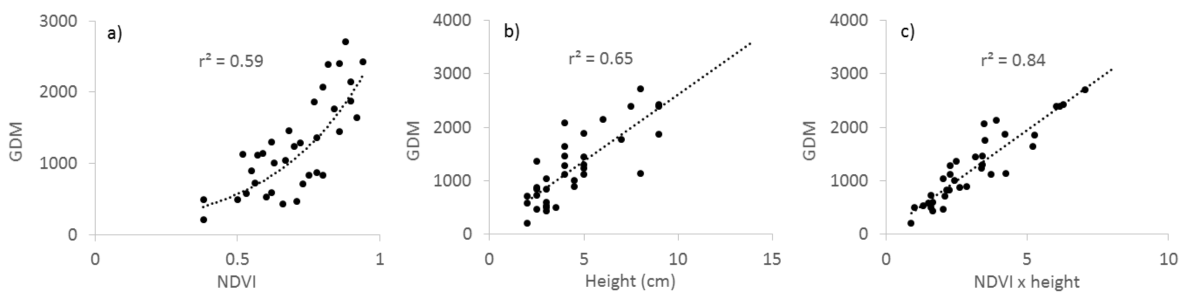

Figure 4-3. Examples of a) 'saturation' in the response between GDM and NDVI; b) typical linear relationship between GDM and height; c) improved correlation of fit between GDM and NDVI x height index.

Overall, the NDVI x height, or NDVI x log(height) models provided the best fits (

Figure 4-4). The log(NDVI) x height and log(NDVI) x log(height) models were the best models in a minority of campaigns, though overall were the poorest models (

Figure 4-4). Across all of the campaigns, the exponential relationship with NDVI, or a liner relationship with either height, NDVI x height, or NDVI x log(height) provided consistently strong results (as indicated by r^2 and CV%). There were seven campaigns where fits of log(NDVI) provided substantially better fits (assessed as an r^2 greater by 0.05 or more) than the exponential NDVI model. In only two of these seven campaigns did log(NDVI) have an r^2 greater by more than 0.1, and the exponential NDVI models still provided acceptable fits and $r^2 > 0.75$. When examined regionally, three of the better fits provided by log(NDVI) was in late spring-summer in Victoria, discussed in the next section. As the remaining models provided no better calibrations or were worse than the exponential NDVI, linear height or linear NDVI x height models, they are not discussed further.

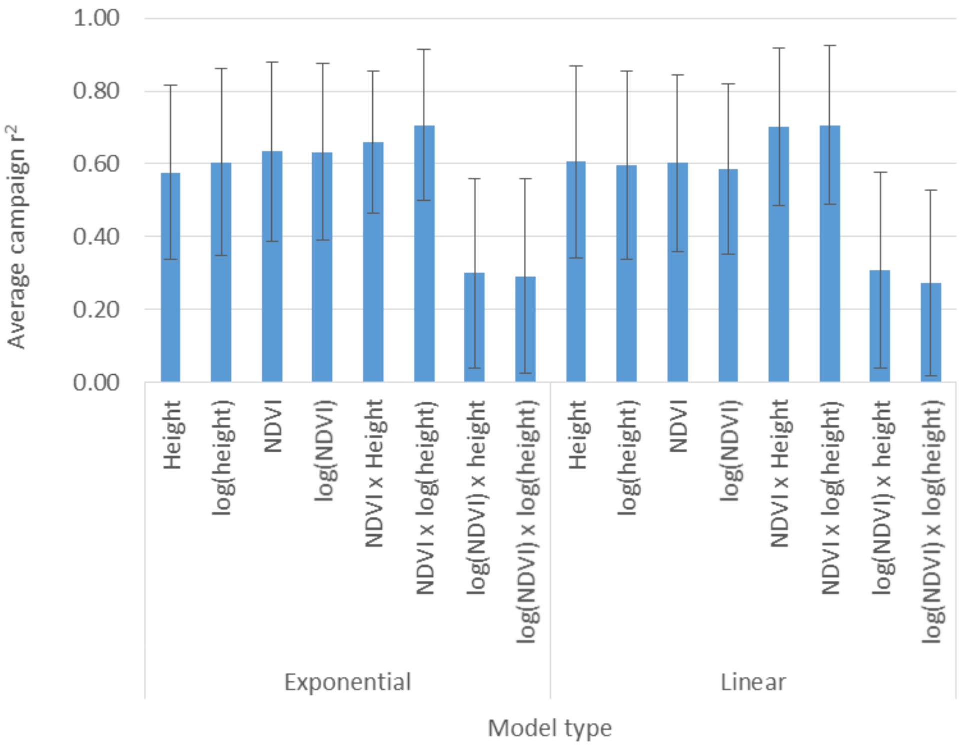

Figure 4-4. Average r^2 of model fits for all campaigns with at least 5 samples. Error bars indicate standard deviation of r2 for each model type across the campaigns.

4.2 Regional campaigns

The following presents the average r^2 of individual campaigns undertaken in the regions, shown for each season and pasture type (temperate grasses, lucerne and clover). In many cases, strong correlations with r2 > 0.9 were found for individual campaigns, though others were some as low as 0.3 to 0.4 (Figure 4-2). The campaigns for the temperate grasses were combined as no difference was found between the calibrations for tall fescue, phalaris, ryegrass and cocksfoot, similar to other findings, e.g. Giepel and Korsaeth (2017). Similarly, some seasons were grouped where the relationships across the campaigns were consistent, such as combined autumn-winter or autumn-spring.

4.2.1 Campaign correlations for NSW

In the NET, the combined indices tended to provide better models for the grass-based pastures than did the height or NDVI alone (Figure 4-5), consistently providing acceptable or good fits (Table 4-1). However, while all campaigns from the grass pastures were satisfactorily modelled, no one model type provided a significant fit for all the campaigns (Table 4-1). Taken separately, height measurements tended to provide better fits than did NDVI (Table 4-1). In contrast, the NDVI alone was more suitable than height for lucerne. However, there were several campaigns where neither single nor combined measure provided a significant fit, and three campaigns when none of the models from

Figure 4-4 provided statistically significant fits (p>0.0.5). Attempts to fit models for clover were also frequently unsuccessful, and while all campaigns were suited by at least one model, they were inconsistent (Table 4-4Table 4-1). These campaigns where significant fits were not provided by the models almost exclusively occurred when the range in height, NDVI and GDM were less than 5 cm, 0.2 units and 1000 kg/ha, respectively. The exception was in one lucerne and one clover, where a variable density of plants in the quadrat gave similar height with the plate meter for a wide range in GDM. The single linear NDVI(LM) model shown for a clover campaign (Table 4-1) had narrow ranges, but the NDVI was centred around the inflexion point of approximately 0.5 where it was not too flat nor too steep, thus allowing some correlation with GDM.

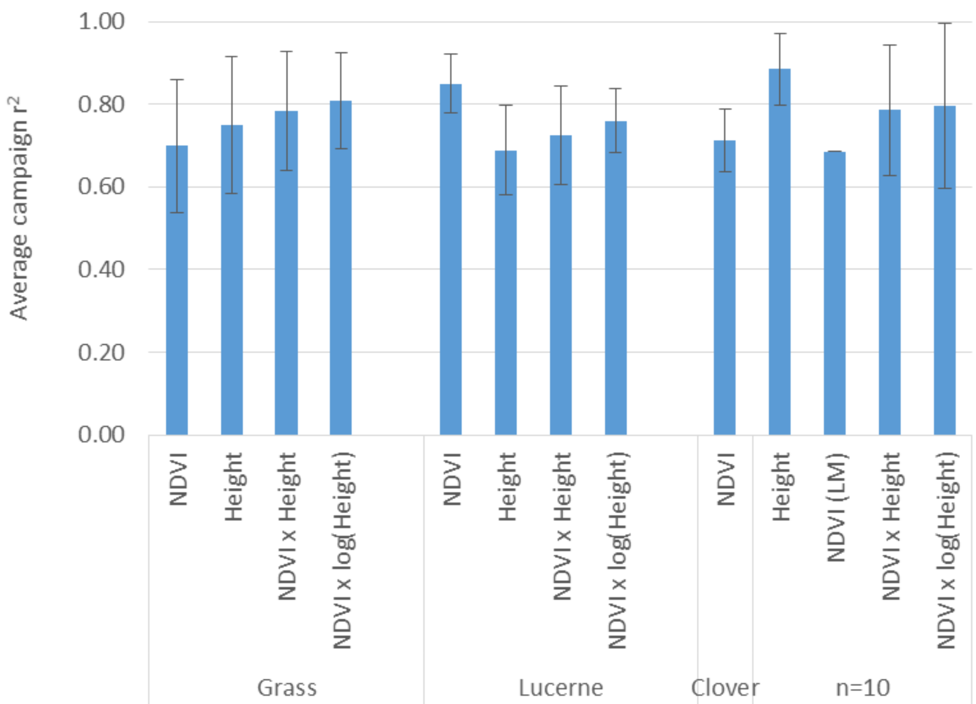

Figure 4-5. Average campaign r^2 of each model for each pasture type at the New England sites. Error bars indicate standard deviation. Height, NDVI x height, and NDVI x log(height) are linear models. NDVI is an exponential model.

Table 4-1. Descriptive statistics for the models for each pasture type in the New England Tablelands of NSW. Height, NDVI x height, NDVI x log(height) and NDVI (LM) are linear models. NDVI is an exponential model.

Pasture type	Model type	n	avg r^2	std. dev r^2	avg CV%
Grass	NDVI	43	0.70	0.16	34
n=48	Height	43	0.75	0.17	23
	NDVI x Height	45	0.78	0.14	21
	NDVI x log(Height)	46	0.81	0.12	21
Lucerne	NDVI	8	0.85	0.07	17
n=14	Height	5	0.69	0.11	17
	NDVI x Height	7	0.72	0.12	19
	NDVI x log(Height)	10	0.76	0.08	15
Clover	NDVI	6	0.71	0.08	12
n=10	Height	3	0.88	0.09	7
	NDVI (LM)	1	0.68	n/a	23
	NDVI x Height	5	0.79	0.16	9
	NDVI x log(Height)	5	0.79	0.20	7

n = the number of campaigns for each pasture and model type.

At the Kingstown sites, six campaigns were collected in each of the tall fescue and lucerne pastures. The data for the fescue was consistent across the seasons so was grouped as autumn to spring. Likewise, the three campaigns on lucerne in winter-spring were consistent so grouped together, as were three summer campaigns. The value in obtaining both NDVI and height was shown by the improved quality of GDM estimates using the combined indices for tall fescue over the corresponding NDVI or height alone (Figure 4-6, Table 4-2). The correlations of NDVI with GDM in lucerne were excellent, and not improved by including height, though there was one campaign where the range of GDM was <600 kg/ha and no model was suitable (Table 4-2).

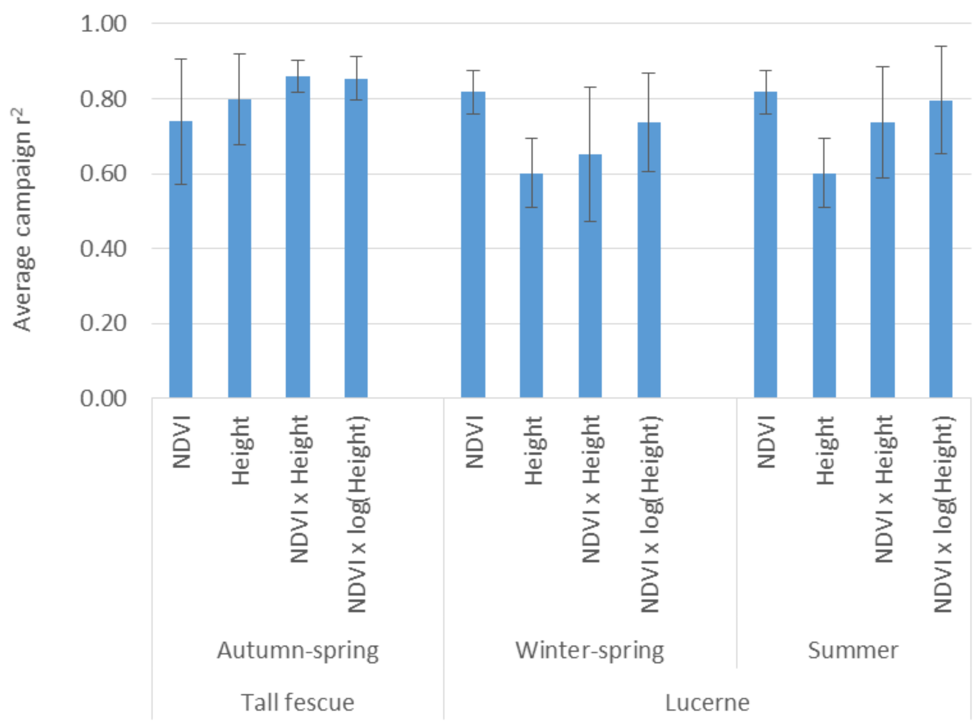

Figure 4-6. Average campaign r^2 of each model for the tall fescue and lucerne pastures near Kingstown in the northern slopes of NSW. Error bars indicate standard deviation. Height, NDVI x height, and NDVI x log(height) are linear models. NDVI is an exponential model.

Table 4-2. Descriptive statistics for the models for the tall fescue and lucerne pastures near Kingstown in the northern slopes of NSW. Height, NDVI x height, and NDVI x log(height) are linear models. NDVI is an exponential model.

Pasture type	Season	Model type	n	avg r^2	std. dev r^2	avg CV%
Tall fescue	Autumn-spring	NDVI	6	0.74	0.17	28
	n=6	Height	6	0.80	0.12	22
		NDVI x Height	6	0.86	0.04	18
		NDVI x log(Height)	6	0.85	0.06	18
Lucerne	Winter-spring	NDVI	3	0.82	0.06	24
	n=4	Height	2	0.62	0.20	30
		NDVI x Height	3	0.65	0.18	24
		NDVI x log(Height)	3	0.74	0.13	21
	Summer	NDVI	3	0.82	0.06	24
	n=3	Height	3	0.60	0.09	27
		NDVI x Height	3	0.74	0.15	21
		NDVI x log(Height)	3	0.80	0.14	18

n = the number of campaigns for each pasture and model type.

Of the seven campaigns (three in winter, three in spring-summer) were conducted in the central-west NSW site near Forbes, five could be modelled (Table 4-3). The low number of campaigns allows only an indication of the usefulness of the technique, but again NDVI x height appears to be suitable, with high r^2 and low CV% (Table 4-3). There were different circumstances for the campaigns that did not have any significant model: one was in summer and had a high height range of 80 cm influenced by tall floret stalks and low NDVI range of 0.1; the second was in winter with low ranges of height, NDVI and GDM of less than 3 cm, 0.2 units and 500 kg/ha, respectively.

Table 4-3. Descriptive statistics for the models for the mixed pastures near Forbes in central-west NSW. Height, NDVI x height, and NDVI x log(height) are linear models. NDVI is an exponential model.

Season	Model type	n	avg r^2	std. dev r^2	avg CV%
Winter	NDVI	3	0.90	0.12	14
n=4	Height	2	0.87	0.04	17
	NDVI x Height	3	0.86	0.12	15
	NDVI x log(Height)	3	0.88	0.08	14
Spring-summer	NDVI	1	0.79	n/a	81
n=3	Height	1	0.96	n/a	23
	NDVI x Height	2	0.89	0.12	23
	NDVI x log(Height)	2	0.67	0.25	45

n = the number of campaigns for each pasture and model type.

4.2.2 Campaign correlations for Victoria

The nine field sites in Victoria were spread across a side area (

Figure 3-1). Except for the summer campaigns, the NDVI was of lesser importance in these phalaris and ryegrass pastures compared to other regions with height models being as satisfactory as the combined NDVI x height indices from autumn through to spring (Figure 4-7, Table 4-4). The poorer fits of NDVI models was due to a generally narrow range. Two campaigns where no suitable model was fitted had low ranges of height, NDVI and GDM, of less than 3 cm, 0.2 units, and 200 kg/ha, respectively.

The comparatively poorer suitability of NDVI t estimate pasture GDM in these Victorian sites compared to other regions reflects the range of values measured. Whereas other sites had a range in NDVI values typically from 0.3 to 0.8 throughout the seasons, the NDVI at the Victorian sites was approximately 0.6 even with very low biomass. This high baseline appeared to be the result of two factors. Firstly, even at low biomass, the pastures had negligible senescent material and were quite fertile. Secondly, the sites were predominantly on dark, basalt derived soils. Where bare ground was visible through the pasture, the low red reflectance from a dark surface results in a high NDVI (Equation 1). The summer campaigns were the exception that proves the rule. Summer was not a targeted sampling season, but hot, dry conditions arrived too early for some spring campaigns. By the time of sampling, the pastures had closed canopies, negating any direct soil influence on the NDVI, and the swards now had a substantial senescent component, allowing the AOS to detect a difference between sample quadrats. Indeed, the NDVI values in these 'summer' campaigns ranged from 0.3 to 0.5. This lower region of the NDVI values is below the typical saturation zone (

Figure 4-3a), so a linear fit of NDVI(LM) was a good fit (Table 4-4).

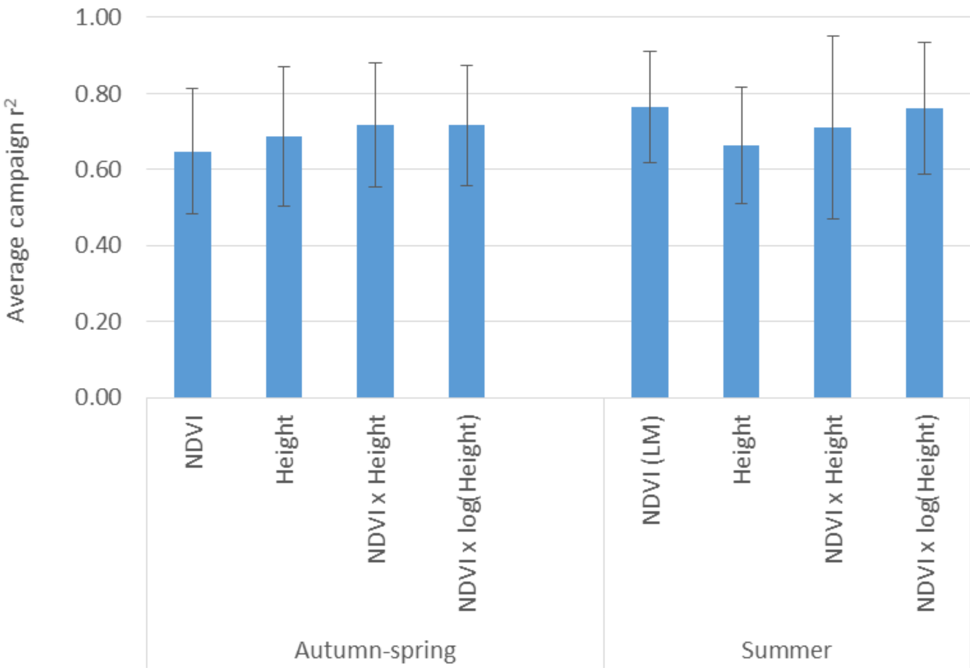

Figure 4-7. Average campaign r^2 of each model for the phalaris and perennial ryegrass-based pastures in Victoria. Error bars indicate standard deviation. Height, NDVI x height, NDVI x log(height), and NDVI(LM) are linear models. NDVI is an exponential model.

Table 4-4. Descriptive statistics for the models for the phalaris and perennial ryegrass-based pastures in Victoria. Height, NDVI x height, NDVI x log(height), and NDVI(LM) are linear models. NDVI is an exponential model.

Season	Model type	n	avg r^2	std. dev r^2	avg CV%
Autumn-spring	NDVI	48	0.65	0.16	26
n=63	Height	57	0.69	0.18	19
	NDVI x Height	58	0.72	0.16	18
	NDVI x log(Height)	58	0.72	0.16	18
Summer	NDVI	6	0.70	0.14	22
n=7	NDVI (LM)	6	0.76	0.15	15
	Height	4	0.66	0.15	16
	NDVI x Height	5	0.71	0.24	14
	NDVI x log(Height)	6	0.76	0.17	15

n = the number of campaigns for each pasture and model type.

4.2.3 Campaign correlations for Tasmania

The NDVI from the AOS was well suited to developing calibrations at the Tasmanian sites, there being only two instances where the NDVI did not provide a significant model (once in spring on the ryegrass, and once on the clover, Table 4-5), on the whole being more reliable than height or the combined indices. Each model type, particularly height, improved in spring when there was a greater range in biomass in the pastures (

Figure 3-1). The linear NDVI model was the best fitted model in an autumn clover, when the pasture was short but the NDVI was high, placing it in the 'saturation' zone above the inflexion point of an exponential graph.

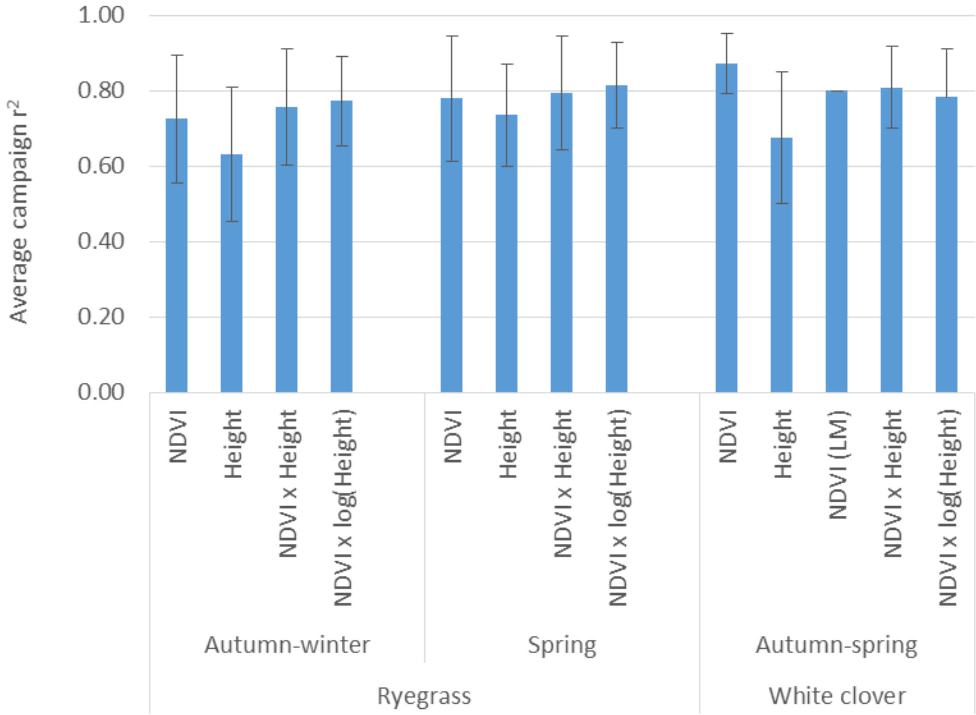

Figure 4-8. Average campaign r^2 of each model for the phalaris and perennial ryegrass-based pastures in Victoria. Error bars indicate standard deviation. Height, NDVI x height, NDVI x log(height), and NDVI(LM) are linear models. NDVI is an exponential model.

Table 4-5. Descriptive statistics for the models for the perennial ryegrass-and white clover pastures in the central midlands in Tasmania. Height, NDVI x height, NDVI x log(height), and NDVI(LM) are linear models. NDVI is an exponential model.

Pasture type	Season	Model type	n	avg r^2	std. dev r^2	avg CV%
Ryegrass	Autumn-winter	NDVI	18	0.72	0.17	28
	n=18	Height	12	0.63	0.18	28
		NDVI x Height	16	0.76	0.15	21
		NDVI x log(Height)	14	0.77	0.12	20
	Spring	NDVI	11	0.78	0.17	20
	n=12	Height	8	0.74	0.14	21
		NDVI x Height	12	0.79	0.15	17
		NDVI x log(Height)	10	0.81	0.11	17
White clover	Autumn-spring	NDVI	7	0.87	0.08	18
	n=8	Height	7	0.68	0.17	25
		NDVI (LM)	1	0.80	n/a	15
		NDVI x Height	7	0.81	0.11	19
		NDVI x log(Height)	7	0.78	0.13	21

n = the number of campaigns for each pasture and model type.

4.2.4 Campaign correlations for Western Australia

Three campaigns were collected on ryegrass and seven on clover at Arthur River in Western Australia. The AOS performed relatively well in these campaigns, providing good $r^2 > 0.7$ (Figure 4-8), however the relative accuracy was only acceptable (CV>30%) in winter (Figure 4-9). In addition, the AOS did not provide a significant relationship in spring for one clover campaign though it did improve the fit through the NDVI x height index (Figure 4-9). GDM was not well correlated with clover height at Arthur River, though it did provide good fits for ryegrass (Figure 4-9).

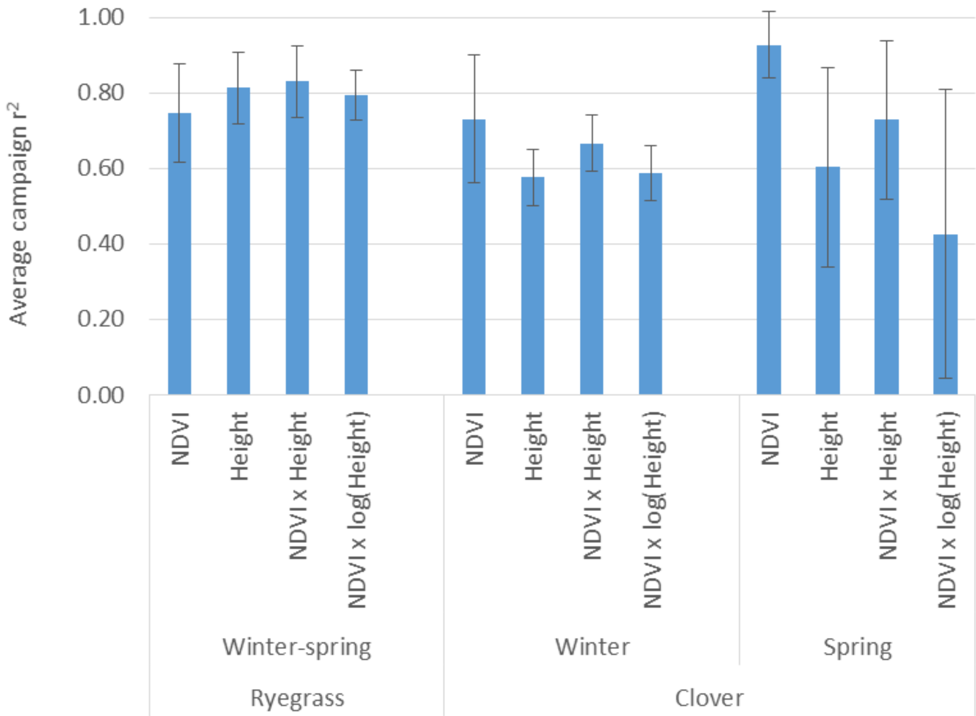

Figure 4-9. Average campaign r^2 of each model for the perennial ryegrass and clover pastures at Arthur River in WA. Error bars indicate standard deviation. Height, NDVI x height and NDVI x log(height) are linear models. NDVI is an exponential model.

Table 4-6. Descriptive statistics for the models for the perennial ryegrass and clover pastures at Arthur River in WA. Height, NDVI x height and NDVI x log(height) are linear models. NDVI is an exponential model.

Pasture type	Season	Model type	n	avg r^2	std. dev r^2	avg CV%
Ryegrass	Winter-spring	NDVI	3	0.75	0.13	19
	n=3	Height	3	0.81	0.09	14
		NDVI x Height	3	0.83	0.10	13
		NDVI x log(Height)	3	0.79	0.07	14
Clover	Winter	NDVI	3	0.73	0.17	31
	n=3	Height	3	0.58	0.07	36
		NDVI x Height	3	0.67	0.07	32

	NDVI x log(Height)	3	0.59	0.07	36
Spring	NDVI	3	0.93	0.09	14
n=4	Height	2	0.60	0.26	15
	NDVI x Height	4	0.73	0.21	16
	NDVI x log(Height)	3	0.43	0.38	28

n = the number of campaigns for each pasture and model type.

4.3 Calibrations for feed estimates

While inspecting the quality of fits available for the individual campaigns of each region is instructive for when the AOS or height measurements are suited to explain the variation in green pasture biomass, providing calibrations requires consistent fits across several years or seasons. The data from the individual campaigns was pooled according to the region/species/season groupings indicated in Section 4.2.

A combined NDVI x log(height) index provided the most suitable calibration for the grass-based pastures in the NET (

Figure 4-10a). Using the combined index improved the r^2 to 0.79 from 0.51 and 0.64 for NDVI and height, respectively. For the white clover, the combined index of 0.88 was an improvement from 0.67 and 0.74 for NDVI and height, respectively (

Figure 4-10b), while NDVI was the most suitable calibration for lucerne (

Figure 4-10c). These models indicate that 79% of the variability in grass based pastures GDM in the NET sites was explained by NDVI and height, similarly 88% for white clover. The NDVI measurements accounted for 66% of the variability in lucerne, though it is worth noting that due to ‘saturation’, above approximately 0.8 and 2500 kg/ha the NDVI is insensitive to change in biomass.

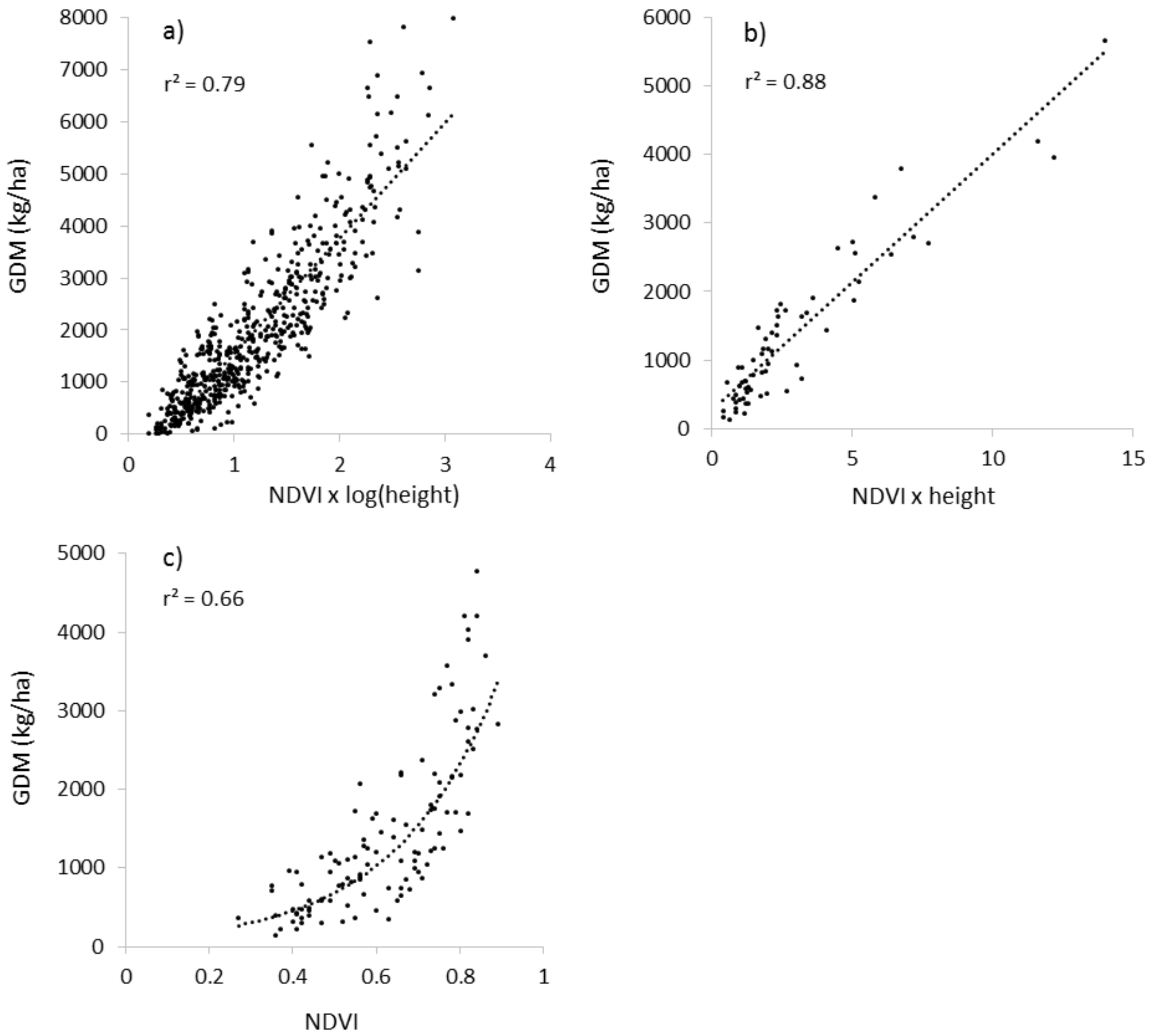

Figure 4-10. Pooled campaign year-round calibration fits for NET a) grass-based pastures, b) white clover, and c) lucerne.

Similar results to the NET were seen in the northern slopes NSW, where the tall fescue pasture was strongly correlated with the NDVI x height index (Figure 4-11a), while NDVI accounted for the variability in lucerne GDM albeit a stronger fit in winter to spring (Figure 4-11b) than in summer (Figure 4-11c). The strength of the relationship between NDVI and lucerne GDM in summer in the northern slopes NSW is significant, but the weakest of any presented here.

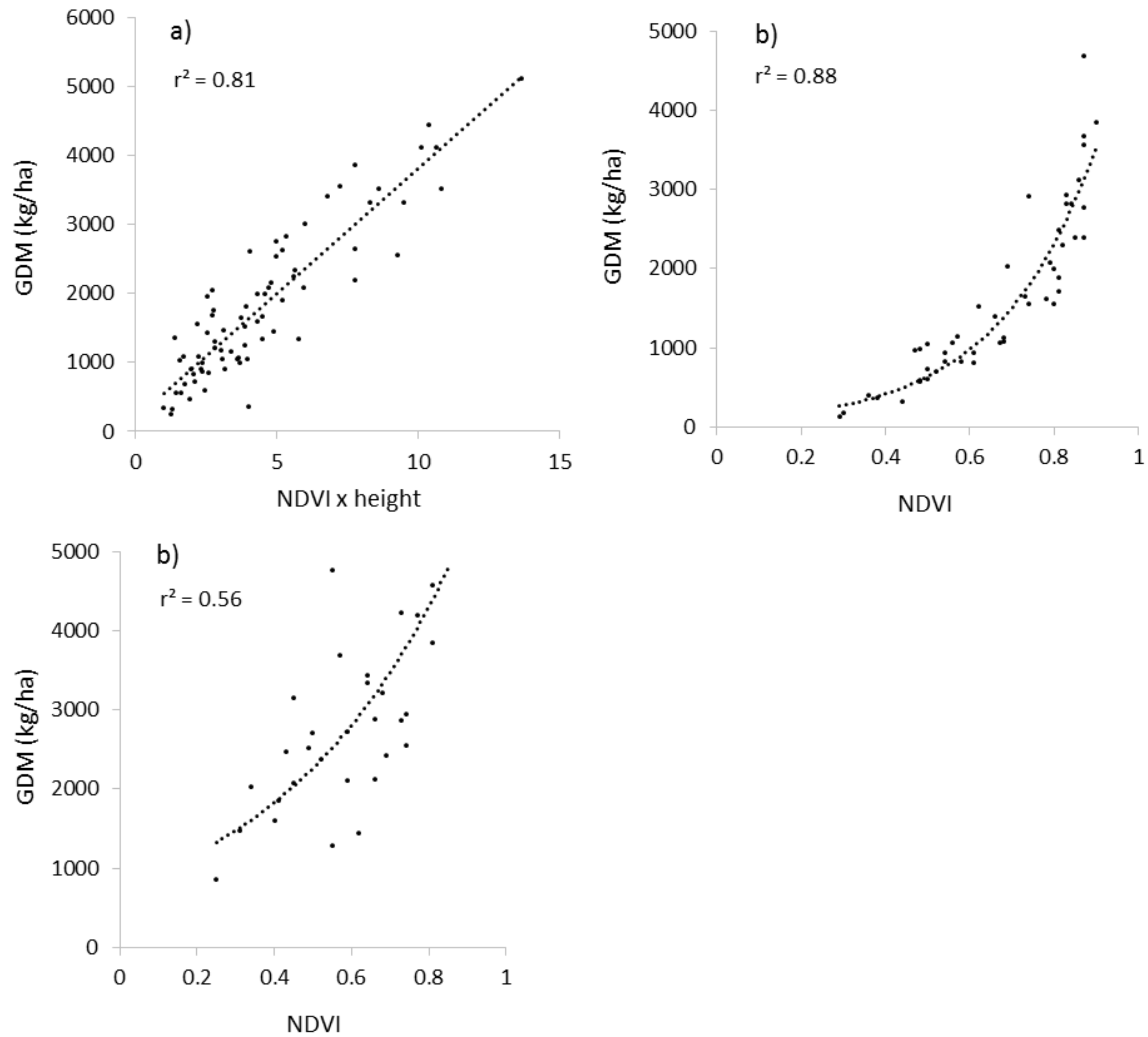

Figure 4-11. Pooled campaign calibration fits for the NSW northern slopes for a) tall fescue in autumn to spring, b) lucerne in winter to spring, and c) lucerne in summer.

The calibrations developed fort the central west mixed pastures relied on NDVI in winter (

Figure 4-12a), then incorporated height with the NDVI x height index in spring to summer (

Figure 4-12b). Though based on fewer pasture cuts, the NDVI 'saturation' in these mixed pastures occurred at a lower GDM than other regions.

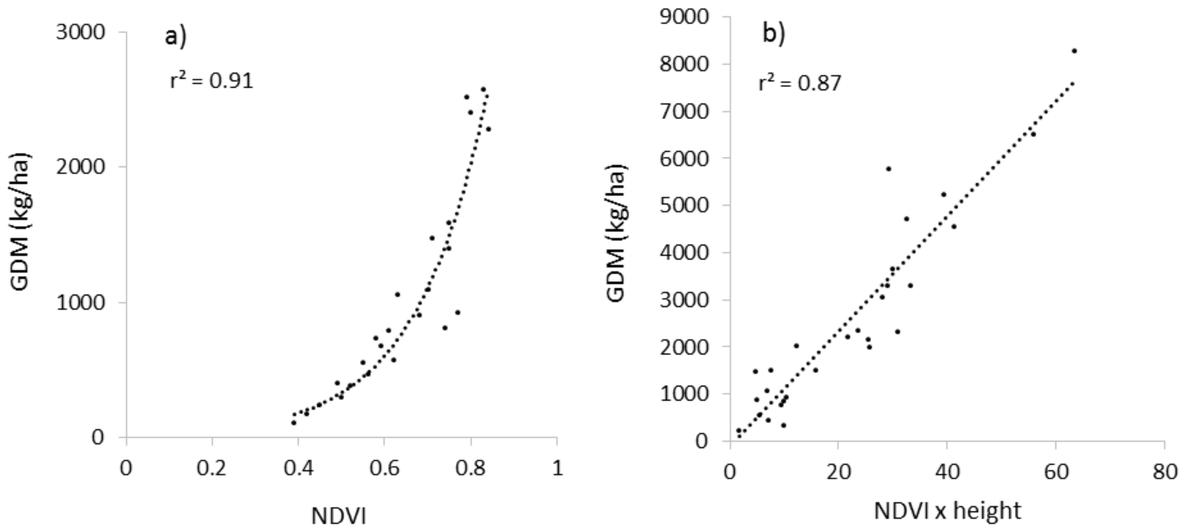

Figure 4-12. Pooled campaign calibration fits for mixed pasture in central west NSW in a) winter, b) spring to summer.

In Victoria, the relationships of GDM to height were consistent for the ryegrass and phalaris pastures, so were combined for the regional calibration. NDVI did not account for a significant variability in GDM, with height explaining 70% of the variability in GDM in autumn to spring (Figure 4-13a). In the late spring-summer cuts, the NDVI did respond to changes in GDM as the pasture canopy closed and there was more senescent material than earlier, leading to the NDVI x log(height) index being used for that seasonal calibration (Figure 4-13b).

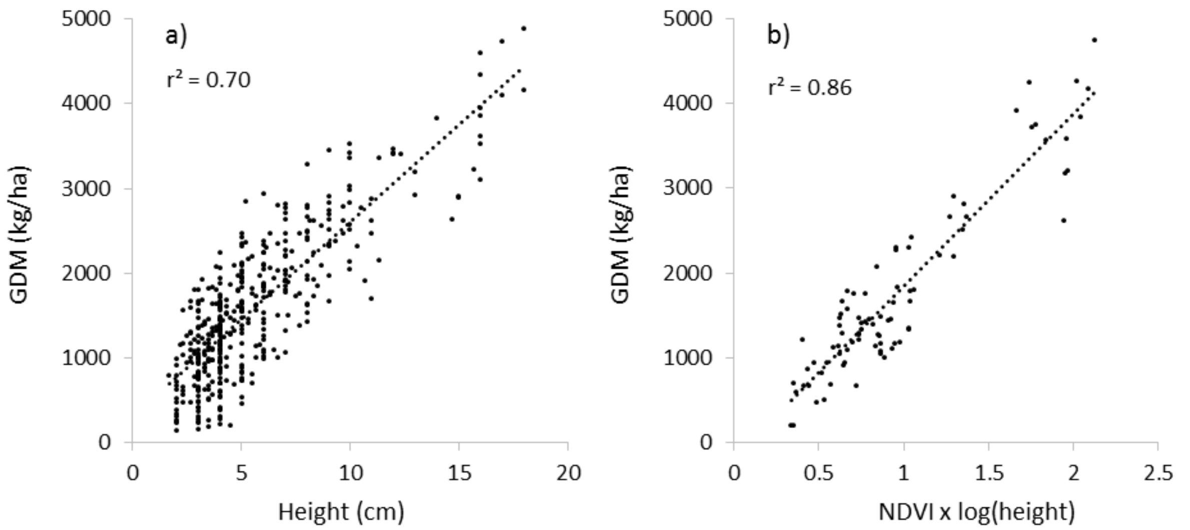

Figure 4-13. Pooled campaign calibration fits for phalaris and ryegrass pastures in Victoria in a) autumn to spring, and b) summer.

The variability in GDM for ryegrass in Tasmania during autumn and winter was well represented by NDVI (Figure 4-14a), with height not contributing significantly. The ability of the NDVI to detect variation in spring waned as the pastures became more consistently green. While a similar proportion of height measurements were in a narrow band in spring as in summer (80% of measurements were between 2 and 7 cm), the lower difference apparent to the AOS resulted in the NDVI x height index as the best calibration, explaining 86% of the variation in GDM of the ryegrass pastures (Figure 4-14b). By comparison, the white clover was best explained by NDVI only from autumn through spring (Figure 4-14c). The sensitivity of the NDVI was again best below approximately 0.8, where it provide an estimate of 2000 kg/ha.

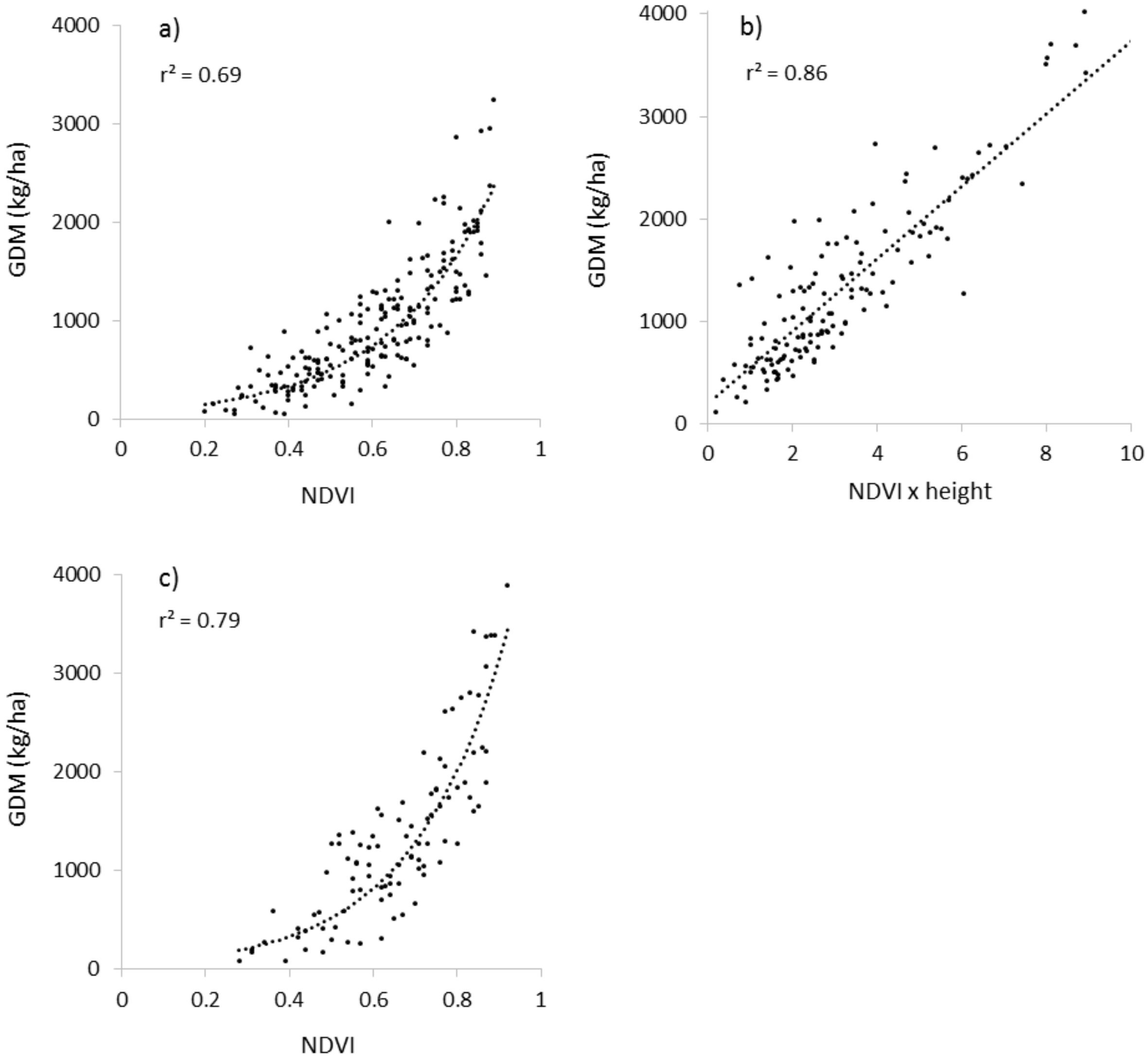

Figure 4-14. Pooled campaign calibration fits for ryegrass pastures in Tasmania in a) autumn to winter, b) spring, and c) white clover in autumn to spring.

The suitable calibrations indicated for WA were of NDVI for clovers (Figure 4-15a and Figure 4-15b), and height for the perennial ryegrass (Figure 4-15c). The calibrations are based only of few results but the models are a similar form to those in other regions. The saturation of the NDVI appears to occur at a lower biomass in these clovers compared to elsewhere, at approximately 1500 kg/ha (spring) to 2000 kg/ha (winter).

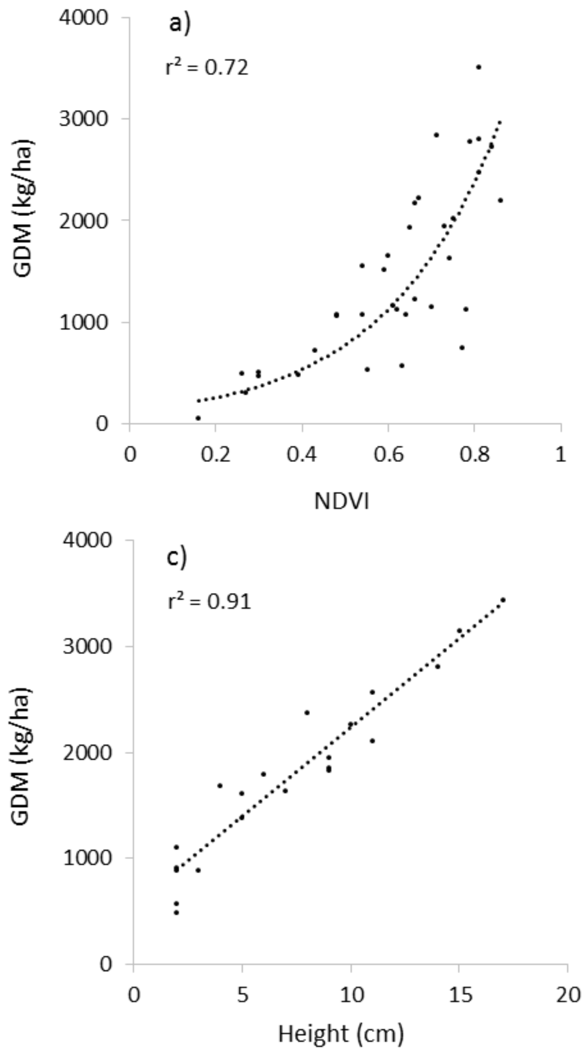

Figure 4-15. Pooled campaign calibration fits for a) clover in winter and b) spring, and c) for perennial ryegrass pastures in winter to spring at Arthur River in Western Australia.

Table 4-7. Coefficient of determination (r^2) number of samples for the selected calibrated models for the pooled data for each pasture/season combination in each region.

	Region	Pasture	Season	Factor	n	r^2
	NET	Temperate grasses	Year round	NDVIxlog(Height)	560	0.79
		White clover	Year round	NDVIxHeight	64	0.88
*				NDVI		0.68
*				Height		0.77
		Lucerne	Year round	NDVI	111	0.66
	Nthn slopes NSW	Tall fescue	Autumn to spring	NDVIxHeight	74	0.81
		Lucerne	Winter to spring	NDVI	48	0.88
*		Lucerne	Summer	NDVI	36	0.56
*	CW NSW	mixed	Winter	NDVI	24	0.91
*		mixed	Spring to summer	NDVIxHeight	28	0.87
	Victoria	Phalaris, per. ryegrass	Autumn to spring	Height	416	0.70
		Phalaris, per. ryegrass	Summer	NDVIxlog(Height)	85	0.86

	Tasmania	Perennial ryegrass	Autumn to winter	NDVI	203	0.69
		Perennial ryegrass	Spring	NDVIxHeight	140	0.79
				Height		0.70
		White clover	Autumn to spring	NDVIxHeight	95	0.79
*				NDVI		0.71
*				Height		0.69
*	Arthur River WA	White clover	Winter	NDVI	40	0.72
*		White clover	Spring	NDVI	17	0.83
*		Perennial ryegrass	Winter to spring	Height	21	0.91

CW NSW = central west NSW (Forbes sites), Nthn slopes NSW (Kingston), NET = New England Tablelands NSW. n = the number of campaigns for each pasture and model type. * indicates a custom calibration.

4.4 Grower estimated biomass

While some producers are skilled at accurately estimating pasture biomass, it not a universal skill. PRGs in Victoria provided visual estimates of pasture biomass. In Tasmania, visual estimates were also made for clover, while the MLA pasture ruler was used for the ryegrass pastures.

Across the phalaris and perennial ryegrass samples collected in Victoria, the eyeball estimates achieved a good correlation, with a 69% accuracy in predicting GDM (Figure 4-16). This compares favourably with the fit established by pasture height (Figure 4-13). However, above approximately 1500 kg/ha the eyeball estimates were increasingly underestimating the actual GDM, so that e.g. by 2300 kg/ha the estimates were on average 300 kg/ha lower than the actual (Figure 4-16). In contrast, estimating the pasture biomass in Tasmania proved more difficult. Using the MLA pasture ruler, the estimated GDM tended to be lower than the actual GDM above approximately 2000 kg/ha (

Figure 4-17a). However, reflecting that height was not as important as NDVI in estimating the actual pasture biomass in these pastures (Figure 4-14), the correlation of the height based ruler estimate was substantially lower than that obtained in Victoria (0.44). The eyeball estimates of white clover in Tasmania were substantially lower than the actual GDM, and similarly inconsistent (

Figure 4-17b).

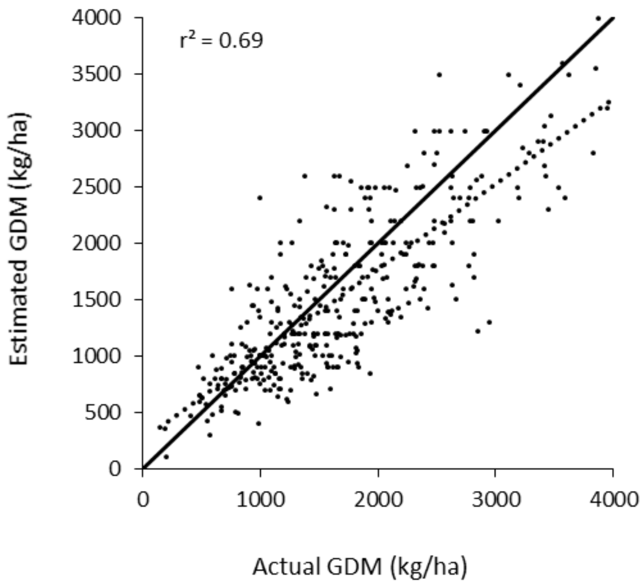

Figure 4-16. Pasture GDM estimates compared to actual GDM for samples collected in Victoria. Solid line indicates 1:1 (actual = estimated). Dashed line indicates line of best fit.

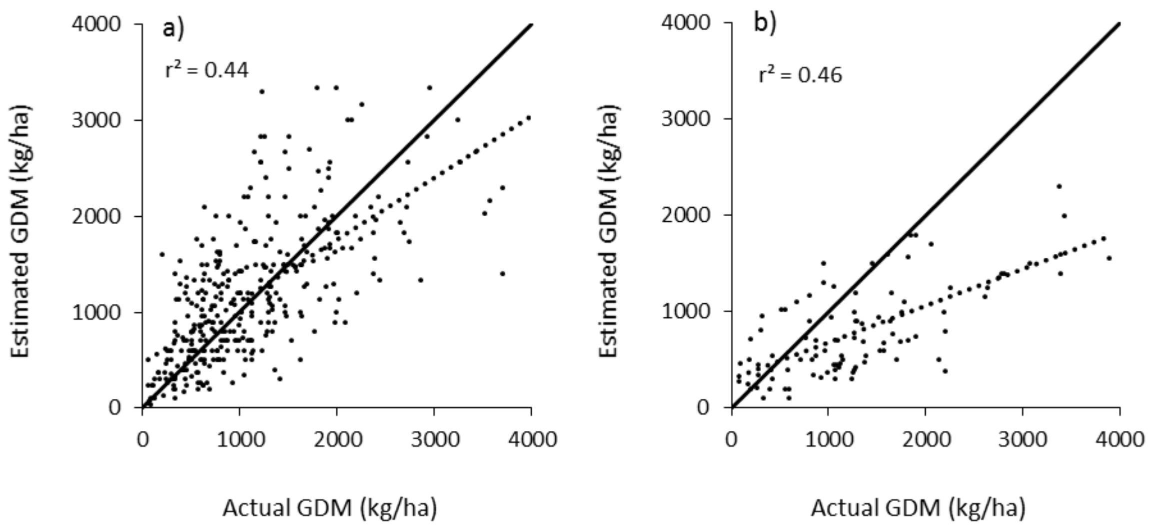

Figure 4-17. Pasture GDM estimates compared to actual GDM for samples collected in Tasmania on a) perennial ryegrass and b) white clover. Solid line indicates 1:1 (actual = estimated). Dashed line indicates line of best fit.

4.5 Comparison of AOS devices

4.5.1 Practicality and accuracy

The Holland Scientific Crop Circle ACS 470 has three separate LEDs and sensors. These can be configured to the user's desired wavelengths by installing appropriate filters. To use the Crop Circle, data is stored on a logger which is then downloaded and processed. The user notes the file number of the log for each site. While more information is stored and provided, it is somewhat cumbersome to use in a field context. In comparison, handheld Trimble GreenSeeker processes the NIR and red responses on board. The NDVI result is provided on the screen for a few seconds for the user to note down, though a data logger app for Android is available (https://play.google.com/store/apps/details?id=edu.okstate.dasnr.trimble&hl=en). While conveniently providing an immediate output, the handheld GreenSeeker is less flexible.

The GreenSeeker and Crop Circle NDVI values were for the most part consistent. However, there were a dozen instances where the GreenSeeker and Crop Circle NDVI values differed by more than 0.1 units. On examination of the site photos, these appeared to occur due to two main reasons: footprint and transcription. The Crop Circle has a rectangular footprint composed of 12 evenly spaced points of focussed light, whereas the GreenSeeker has an oval footprint with a denser response at the centre. Most of the substantial (>0.1 unit) differences in NDVI readings between the two AOS were due to the combination of a variable target (patchy distribution of senescent material or bare ground) and the differing footprint. Where this occurred, a judgement of which reading to use was made after comparing site photos. Where no difference was noted in the photos, the difference appears to have arisen due to recording the wrong Green Seeker reading or Crop Circle file number.

One circumstance where the Crop Circle was clearly superior to the Green Seeker in the field was where the GreenSeeker failed to provide a value. A number of instances occurred where the GreenSeeker gave a reading of “E_F”. This “error – far” occurs when the on-board sensor does not detect a strong enough signal from either the red or NIR to make the NDVI calculation. This error occurred on dark soils, which by their nature reflect little red light. Most of the E_F data occurred on the post-cut site. Some of the E_F readings occurred on the pre-cut sample where the sample area was predominantly bare dark soil.

A second circumstance where the Crop Circle is superior to the Green Seeker regards two aspects of data consistency. Firstly, unit calibration. The lenses of the emitter or detector can become scratched over time. This will affect the passage of light to the unit, so influencing the apparent NDVI. In addition, it is likely that the emitters and detectors will drift over time, again influencing the apparent NDVI. To overcome this, there is a procedure to calibrate the Crop Circle against absolute standards and reset the unit to maintain consistent readings. However, there is no similar procedure possible for the GreenSeeker. This lack of unit calibration is a potential problem considering some that there is some variation between GreenSeeker units.

4.5.2 Analysis of additional bands and indices compared to NDVI

Two Crop Circle ACS 470 units were used at the Armidale sites, providing six wavelengths to assess their potential to provide reliable estimates of GDM (Table 4-8). The context for assessing the four bands in addition to the standard Red and NIR was that while the ACS 470 is more a research instrument, commercial instruments containing other bands are on or near to market.

Table 4-8. Wavelengths collected using the Crop Circle ACS 470.

ACS470 band	Nominal wavelength (nm)
Green	530
Yellow	590
Red	670
Red2	700

Red edge	730
NIR	760

A comparative analysis of the options provided by the AOS and plate height data was conducted after the first 36 campaigns were completed. A simple ratio for each combination of two of the six bands was derived for 36 sites (temperate grasses and lucerne) using Excel. An equivalent NDVI for each of the shorter five bands was also calculated with NIR. Individual band data was included in the analysis, though using single bands are problematic as unlike the ratios they are influenced by height above the surface. A step wise regression was then performed on the ratios and bands in JMP.

The data were analysed first as a combined dataset, with an r^2 of 0.46 for the simple ratio of red2/red and NDVI (Table 4-9). The 2-band option was almost as food as the 3 band option on all the data. For the temperate grasses, the 3-band option was better than the 2-band option and GreenSeeker, though not better than height (r^2 = 0.64, Table 4-9). Conversely, the 3-band model was the best for Lucerne, marginally better than the 2-band model and Greenseeker, with the height model not well suited (Table 4-9).

Table 4-9. Summary of r^2 for best models for temperate grasses and for lucerne produced by step wise regression of 2 and 3 band combinations all 6 bands available and of simple ratios using the Crop Circle ACS 470. The corresponding best models for plate height and GreenSeeker NDVI are also shown.

Pasture type	n	Bands	Model	r^2
All data	368	2	Ln GDM = Ln NDVI((760-700)/(760+700))	0.44
		3	Ln GDM = SR (700/670), Ln NDVI ((760-700)/(760+700))	0.46
Temperate grass	222	2	Ln GDM = SR(730/760)	0.37
		3	GDM = SR(730/670), SR(730/700)	0.51
			GDM = f(Height)	0.64
			Ln GDM = f($NDVI_{GS}$)	0.29
Lucerne	73	2	Ln GDM = Ln GNDVI ((760-530)/(760+530))	0.82
		3	Ln GDM = SR (590/700), Ln NDVI((760-700)/(760+700))	0.88
			GDM = f(Height)	0.56
			Ln GDM = f($NDVI_{GS}$)	0.70

SR = simple ratio, GNDVI = Green NDVI, $NDVI_{GS}$ = NDVI measured by GreenSeeker

For the first 36 individual campaigns, the additional bands provided by the two Crop Circle units, stepwise regression showed that three band combinations from the ACS470 provided consistently better fits than did the GreenSeeker and plate height (Table 4-10).This indicates the potential for the additional bands to provide estimates of GDM, however the best fit was a combination of any of the six bands, not just of the three available on one of the two Crop Circle unit. Overall, the combination of simple GreenSeeker NDVI and the plate height consistently provided strong results (Table 4-10).

Table 4-10. Percentage of the first 36 campaigns with r^2 greater than 0.8 provided by 2 or 3 band combinations all 6 bands available using the Crop Circle ACS 470, using the GreenSeeker, or height or the GreenSeeker and height together.

Sensor or sensor combination	Proportion of sites with an r^2 above 0.8
ACS 470 2 band optimised model	67%
ACS 470 3 band optimised model	86%
GreenSeeker NDVI	39%
Height	31%
GreenSeeker NDVI and height combined	78%

To compare the AOS and plate height across the first 36 campaigns, an increase in r^2 for the correlation of GDM to sensor/combination of more than 0.1 was considered to be a substantive improvement. For nearly all sites, an optimised model from the ACS 470 bands was the best, and in 71% of these sites was considered a substantive improvement (Table 4-11). The best ACS 470 combination was again generally better than the best model from the GreenSeeker, height or a combination of both, but in only 29% of these sites was is a substantive improvement (Table 4-11).

Table 4-11. Percentage of the first 36 campaigns where the ACS470 bands had a better correlation with pasture green dry matter compared to GreenSeeker, height or a combination of both.

Question	% of sites
Proportion of sites where ACS470 bands are better than GS NDVI?	97%
Proportion of these sites where there is a substantive improvement (increase of $r^2 > 0.1$)?	71%
Proportion of sites where ACS470 bands are better than GS NDVI, Height or a combination?	78%
Proportion of these sites where there is a substantive improvement (increase of $r^2 > 0.1$)?	29%

4.5.3 Consistency and reliability of the GreenSeekers

The biomass noted a difference in the readings of some of the GreenSeekers over the same pasture. The GreenSeekers that the team have were from two main batches, one set obtained early in the project, and a second batch obtained mid-term. Standard materials were obtained to cover the NDVI from approximately 0.1 to 0.9. Substantial differences (up to 0.08 units) were measured in the region from 0.5 to 0.9, which is a key response zone for pastures. The difference between the units appears to be related to the batch; whether this was intrinsic to the units' manufacture, a drift, or the accumulation of wear and tear remains for clarification.

4.6 Pasture quality

Following interest from PRGs, a selection of pasture samples were tested for standard quality parameters by FeedTest in Werribee, Victoria. The parameters tested were crude protein (CP, % DM), acid detergent fibre (ADF, % DM), neutral detergent fibre (NDF, % DM), digestibility (Dig., % DM), metabolisable energy (ME, MJ/kg DM), water soluble carbohydrates, (WSC (%DM), fat (% DM), and ash (% DM). The samples selected for testing were from seven cuts taken in a phalaris pasture over a period of 5 months in 2016. These particular cuts were sampled as upper and lower portions of the sward, and sorted into green and senescent components as usual, yielding four subsamples per quadrat, though not enough dry matter remained for testing of two lower samples. Some of the samples were tested by wet chemistry as they were off scale for ash%; these were the senescent fractions of the upper portions in June and August, and the senescent fractions of the lower portions of the sward in October and November. The samples were dried and ground to <1 mm and stored in cool dry conditions prior to testing.

In general terms, the CP, Dig and ME were greater in the green fraction and the upper portion of the sward than the senescent fraction and lower portion of the sward. The ADF, NDF and ash were greater in the senescent than the green fractions. No significant trend was evident for WSC or fat. The mass weighted average of each attribute (green and senescent material) reveal significant ($p < 0.05$) positive trends for NDVI against CP ($r^2 = 0.30$, $p<0.05$), Dig. ($r^2 = 0.67$, $p<0.001$), and ME ($r^2 = 0.68$, $p<0.001$), and negative trends for ADF ($r^2 = 0.73$, $p<0.001$), NDF ($r^2 = 0.67$, $p<0.001$) and ash ($r^2 = 0.67$, $p<0.001$) (Table 4-12). No significant relationship was observed for WSC or fat.

Table 4-12. NIR or wet chemistry pasture quality results for phalaris.

site	date	layer	NDVI	CP	ADF	NDF	Dig.	WSC	Fat	Ash	ME MJ/kg DM
							%DM				
1	3-Jun	U	0.82	28.4	21.2	42.1	81.3	8.9	4.1	8.5	12.3
2	3-Jun	L	0.66	22.1	27.0	48.6	68.6	7.4	3.9	15.4	10.2
3	4-Jul	U	0.82	26.8	26.5	48.3	75.9	6.9	3.9	13.8	11.5
4	4-Jul	L	0.6	17.7	34.0	56.8	63.4	4.7	3.4	18.3	9.3
5	15-Aug	U	0.62	20.3	25.8	48.8	64.7	11.1	3.6	12.8	9.5
6	25-Oct	L	0.74	16.9	25.2	47.9	78.2	18.2	3.7	9.6	11.9
7	25-Oct	U	0.57	8.7	31.7	49.8	56.2	19.8	3.5	12.1	8.1
8	4-Nov	L	0.75	15.3	26.7	49.0	74.8	16.2	3.5	10.5	11.2
9	4-Nov	U	0.55	11.0	29.5	51.8	62.4	14.2	3.4	10.7	9.1
10	10-Nov	L	0.75	13.9	27.7	53.1	73.9	15.8	3.4	9.1	11.1
11	16-Nov	U	0.77	15.3	24.5	44.8	62.1	8.1	2.9	10.6	9.3
12	16-Nov	L	0.57	10.6	33.6	54.5	55.4	8.9	3.3	16.2	7.9

U = upper and L = lower portion of the sward, respectively.

4.7 Mobile Device Application development

The MDA was developed on an Android platform by the HITLabNZ (human interface technology laboratory) at the University of Canterbury, New Zealand. The development was primarily done by Dr Gun Lee, with direction from the UNE team.

4.7.1 Architecture

The development of Biomass MDA involves two main components: the application and a server. The MDA is used to estimate GDM using calibrations based on NDVI readings from a handheld sensor and pasture height. The calibration formulae are downloaded from the server over an internet connection and cached on the mobile device for offline use. The usage log and custom calibration information are uploaded on the server. The administrator is able to access the server through a web interface to monitor usage statistics and manage/update the calibration formula (Figure 4-18).

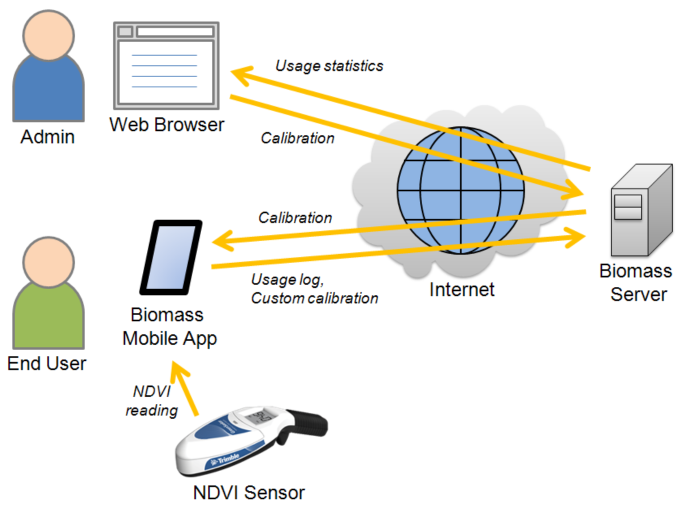

Figure 4-18. Schematic representation of the MDA architecture.

4.7.2 Technology

4.7.2.1 Biomass Mobile Device Application

The MDA was developed on the Android mobile platform (http://developer.android.com), with minimum v4.0.3 (API Level 15). The MDA, titled "Biomass", was made available through the PlayStore. The Android platform was suitable for the MDA development, particularly for investigating and exploring advanced features such as wireless communication between NDVI sensor and the mobile device, paddock mapping through Google Maps Android API v2, and to provide a custom MDA hardware pack. A web based platform was ruled out at the beginning of the project as it would require data connection in the field.

4.7.2.2 Biomass Server

The Biomass server is fundamentally a Java Servlet (v2.5 or later) based web server. Communication between the mobile device and the server is through HTTP-based representational state transfer (REST) style API. The data exchanged between the mobile device and the server is formatted in Json (http://json.org). The server is hosted on the Google Cloud Platform App Engine (https://cloud.google.com/appengine/docs), using the Datastore service for data storage.

The web-based interface for administrators for managing the server is based on web standards including HTML, CSS, and JavaScript. The interface also uses JSP (http://www.oracle.com/technetwork/java/jsp-138432.html) for integration between the web interface and the Java Servlets.

4.7.3 Screenshots and features

The first point of entry after installing the Biomass MDA is a registration page, which collects user information to support analytics of future use, most importantly the likely quality self-calibration data. Once installed, the user proceeds to the main features of the MDA which include a feed estimate, paddock history, and self-calibration. The features are supported by the training modules. The screens to access the features in the MDA follow.

4.7.3.1 Start page

The start screen introduces the Biomass MDA, and with the help files it includes a message that the MDA can be used to obtain estimates of pasture biomass from regional calibrations, or can incorporate new data for a self-calibration. The user can navigate to the ‘Feed Estimate’, ‘Set up paddocks’, and ‘Farm history’ sections. Where a calibration does not their situation, the user is directed to develop their own Figure 4-19.

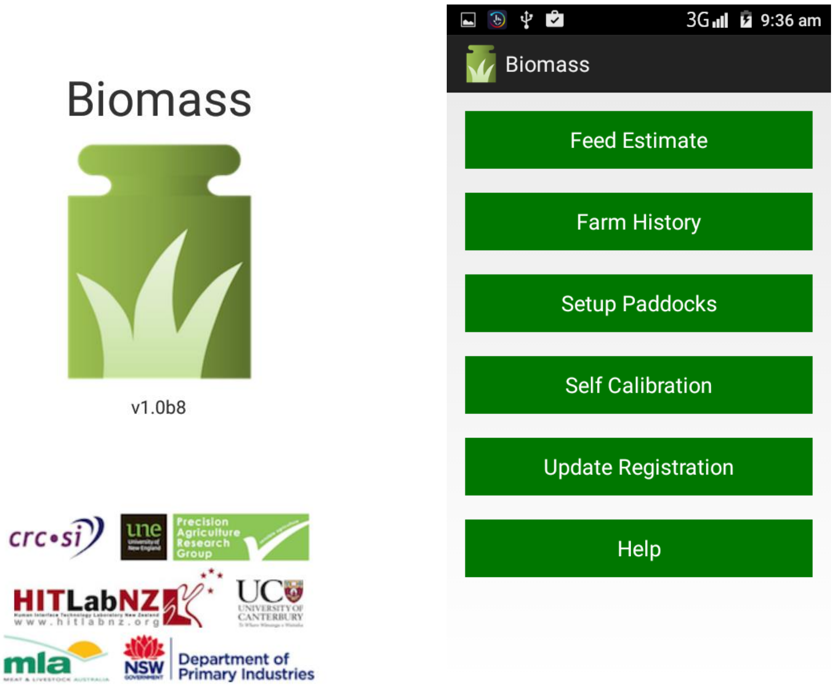

Figure 4-19. The start screens of the Biomass app.

The introductory help document briefly explains how to collect data to use the MDA (measure height with a falling plate and NDVI by holding a Trimble GreenSeeker 1 m over the target area) before directing the user to the ‘Feed estimate’ and ‘Self-calibration’ sections for detailed descriptions on collecting data and using the app.

4.7.3.2 Feed estimate

In the ‘Feed Estimate’ section, the MDA provides estimates of pasture biomass GDM that have been calibrated for the regional/seasonal/species indicated Section 4.3. To use the feed estimate, users select the region, species and season from the drop down menus. The region and species can be short-cut by selecting a paddock a paddock already described, and then selecting the season. After entering the NDVI and height the estimate of the pasture biomass (in kg green dry matter per hectare) appears (Figure 4-20). When the paddock for this feed estimate has been described in the ‘Set up paddocks’ section, the feed estimates can be saved to paddock history, then monitored through the ‘Farm history’.

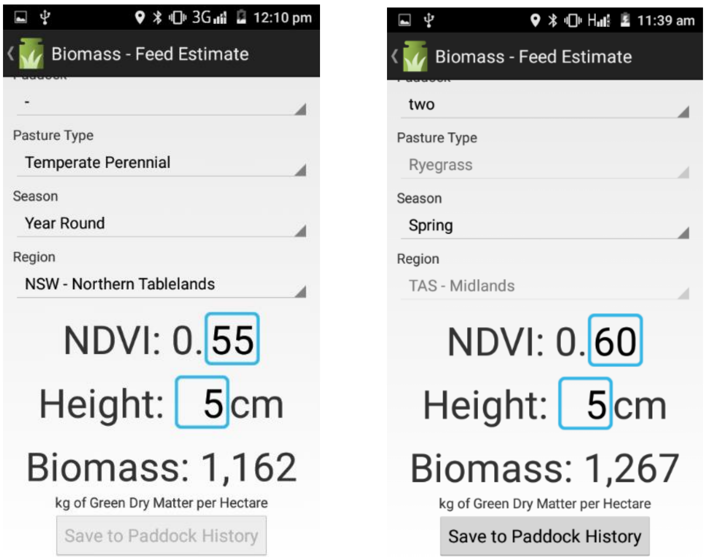

Figure 4-20. The feed estimate screens.

Where a suitable calibration is not available, users are directed to the self-calibration section of the MDA to develop their own.

4.7.3.3 Set up paddocks

Setting up a paddock is a simple process of specifying the paddock name, its pasture type, and region (Figure 4-21). Estimates of pasture biomass can then be saved, and viewed through ‘Farm history’.

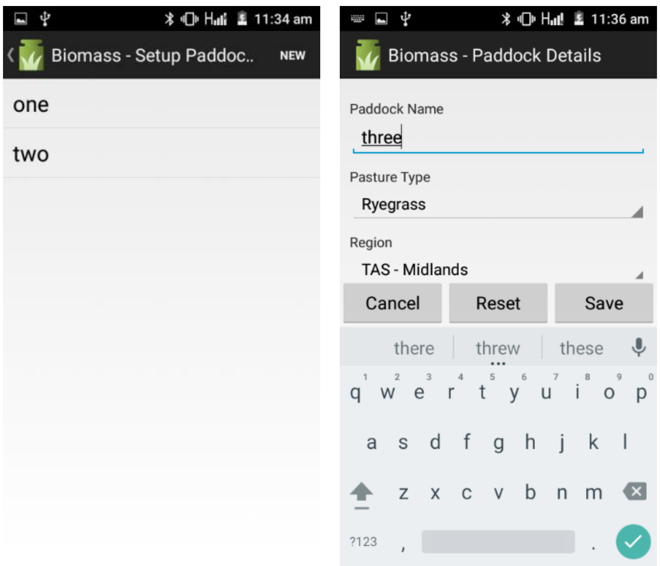

Figure 4-21. Setting up paddocks.

4.7.3.4 Farm history

‘Farm history’ lists all paddocks that have been defined, with the history of feed estimates made for each paddock along with the quantity and rate of change in between estimates (Figure 4-22).

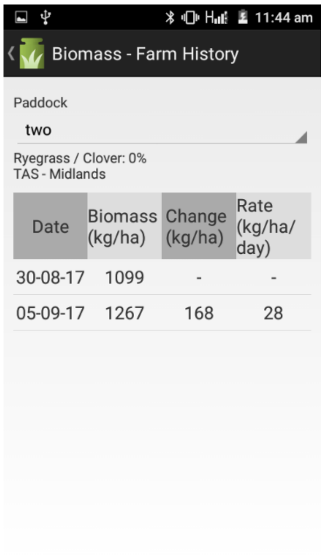

Figure 4-22. Viewing the history of feed estimates.

4.7.3.5 Self-calibration

Where a suitable calibration is not available to suit the user's situation, they can develop their own. Self-calibrations can be created based on their own measurements, though the MDA also supports an experienced user choosing to create their own by eye. Calibrating by taking pasture cuts is a two-step process. The first involves collecting data in the paddock, the second is sorting and drying the pasture samples. The MDA will takes the user through the process of selecting sample locations, taking measurements and collecting the pasture. All the data can be entered directly into the MDA to generate a custom calibration. The MDA allows for different sized quadrats to be used, as well as adjusting for any inadvertent inclusion of soil that is difficult to remove from a sample (Figure 4-23).

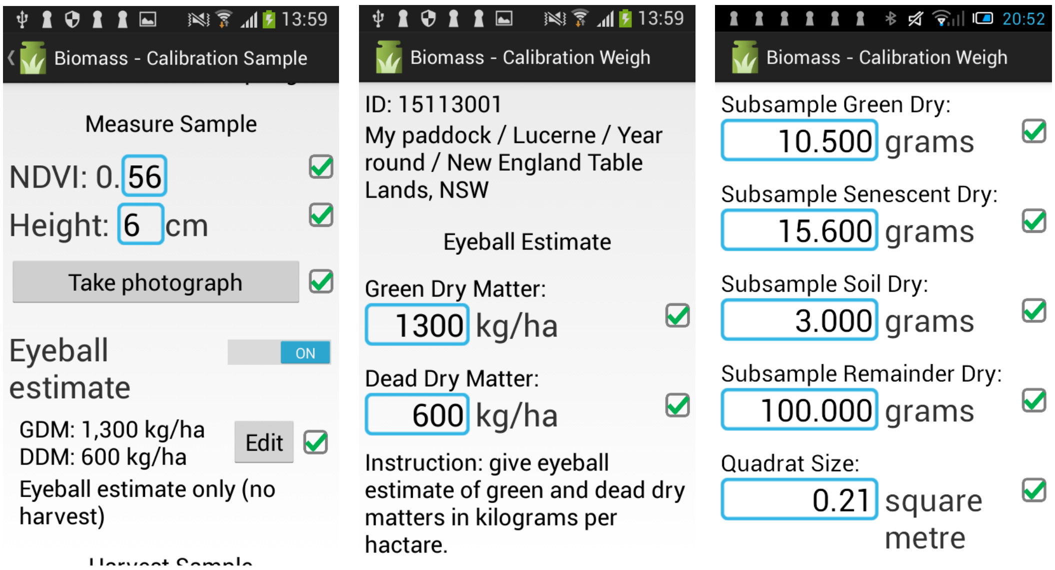

Figure 4-23. The self-calibration screens.

4.7.4 Crowd-sourcing protocol

The crowd-sourcing protocol was developed to guide how data can be used to develop new calibrations or refine existing calibrations in future (Figure 4-24). This process details the steps that are to be taken when assessing self-calibration data to provide a custom calibration back to the user. The secondary purpose for the self-calibration data is to potentially create new regional/seasonal/species specific calibrations. Where the data is assessed as reasonable, it can be set aside to be pooled to develop new, or refine existing calibrations.

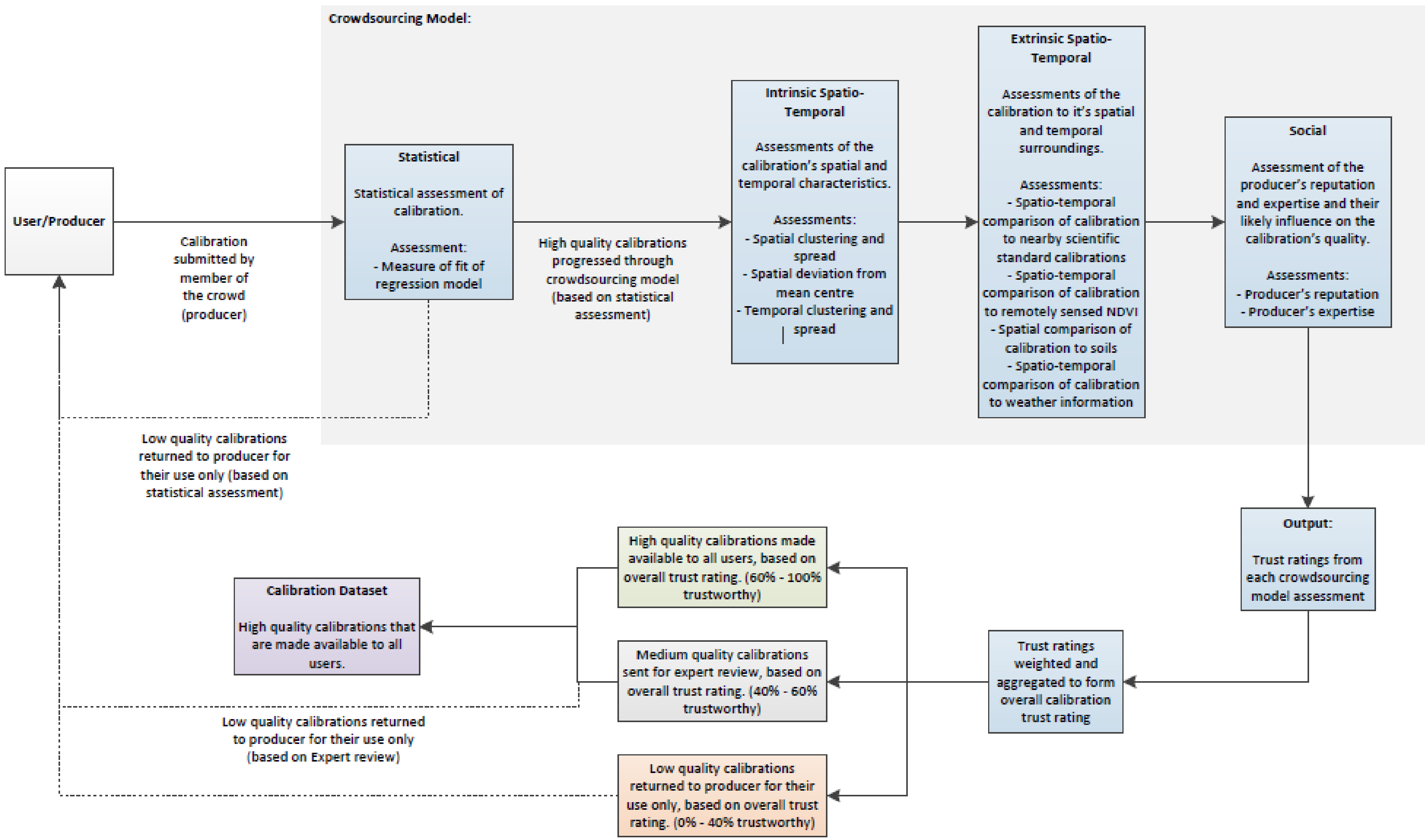

Figure 4-24. Crowd-sourcing protocol for incorporating externally-sourced data into feed estimate calibrations (source: Paul Goodhue and Dr Femke Reitsma, UC, New Zealand).

4.7.5 Quadrat comparisons

Users who may potentially contribute crowd-sourced data could use different quadrat sizes to that used by in this project. While our 30 cm x 70 cm quadrat was designed to include the different footprints of the GreenSeeker and the Crop Circle, it is not a common size or shape for pasture research. A more common size is a 50 cm x 50 cm quadrat. In order to ensure that data could be matched between the two quadrats, we undertook investigations to compare the GDM and TDM harvested from both. To do this we overlaid the quadrats and collected pasture into three separate bags: the central overlapping section, the long edges where the 50 cm quadrat hung over the 30 cm edge, and the short edges where the 50 cm quadrat was inside the 70 cm edge. We collected pasture cuts this way from 32 sites of phalaris and ryegrass pastures. The collected pastures were sorted and weighed in the usual manner, and the weights added up.

The results of the ryegrass cuts were quite consistent between the two techniques (Table 4-13). The GDM of all bar three samples differed by less than 10%, with an average absolute difference of 6% for GDM and 4% for TDM. By comparison, there was more discrepancy in the phalaris cuts (Table 4-14). The phalaris cuts were done first, and after reviewing the photos, the technique was tightened. Indeed, it could be noted in the photos where some pasture had been inadvertently left behind that may have contributed to the difference. The difference in the quadrats means a 20 cm x 50 cm area is harvested from the square quadrat only. For this area, leaving one g of pasture (dried) will lower the measured weight by 100 kg/ha. Leaving the same amount in the 20 cm, x 30 cm area of the long quadrat will lower the weight by 167 kg/ha. These DM differences are in the region estimated as potential errors at the outset of the project (Mark Trotter, pers. comm.).

Table 4-13. Green dry matter (GDM) and total dry matter (TDM) of perennial ryegrass measured using two overlapping quadrats, and the absolute differences in kg/ha and %.

Sample	30*70 quadrat		50*50 qudrat		Absolute difference			
	GDM	TDM	GDM	TDM	GDM	TDM	GDM	TDM
		kg/ha			kg/ha		%	
1	2654	3924	2726	3960	72	36	3	1
2	2831	4105	2588	3800	243	305	9	7
3	2910	4657	3104	4852	194	195	7	4
4	3168	4343	3093	4444	76	101	2	2
5	3865	5367	4092	5452	226	85	6	2
6	4295	5833	3769	4964	526	869	12	15
7	2652	3824	2635	3892	18	68	1	2
8	2687	4067	2558	3696	129	371	5	9
9	2452	3895	2531	3808	79	87	3	2
10	2678	4657	2426	4564	251	93	9	2
11	2586	3490	2499	3496	87	6	3	0
12	3776	5200	3967	5288	191	88	5	2
13	1951	3010	1730	2776	221	234	11	8
14	2163	3519	2384	3756	220	237	10	7
15	1955	2995	2007	3100	52	105	3	3
16	2226	2929	2188	2940	38	11	2	0
Average					164	181	6	4

Table 4-14. Green dry matter (GDM) and total dry matter (TDM) of phalaris measured using two overlapping quadrats, and the absolute differences in kg/ha and %.

Sample	30*70 quadrat		50*50 qudrat		Absolute difference			
	GDM	TDM	GDM	TDM	GDM	TDM	GDM	TDM
		kg/ha			kg/ha		%	
1	1607	5271	1496	4956	110	315	7	6
2	1760	3867	1595	3592	165	275	9	7
3	1543	4257	1359	3956	184	301	12	7
4	1211	3248	1069	2868	142	380	12	12
5	1164	2733	1377	3420	214	687	18	25
6	2598	5786	2171	4976	426	810	16	14
7	1631	4090	1566	4008	65	82	4	2
8	1040	2805	1181	3048	141	243	14	9
9	2004	4676	1979	4436	25	240	1	5
10	1693	4610	1742	4408	50	202	3	4
11	817	3119	650	2832	166	287	20	9
12	1513	3633	1507	3692	7	59	0	2
13	2342	5495	2428	5844	86	349	4	6
14	1872	4629	1968	4736	95	107	5	2
15	2039	6329	2089	6468	50	139	2	2
16	1257	3043	1188	2980	69	63	5	2
Average					125	284	8	7

4.8 PhD student and research fellow

4.8.1 PhD student

Mr Paul Goodhue was enrolled as a PhD candidate under the project, undertaking research in the field of crowd-sourcing data analytics. Paul was under supervision from Dr Mark Trotter and Dr Femke Reitsma. A change in supervision led to a delay in Paul's completion.

During the project, the need for a convenient method to measure height became evident. An automated measure of height, ideally collected simultaneously with the NDVI readings, could provide a better and more convenient GDM estimate could be achieved. Preliminary research into using a lidar was undertaken during 2015 by Mr Morgan Chau, an undergraduate student project at UNE. Promising results encouraged Morgan to commence a Masters project in 2017. The research will include work developing a prototype for field deployment to measure both the dead and green fractions of total biomass. Morgan is enrolled part-time, so his research will continue beyond the completion of the project.

4.8.2 Research fellow

Dr Andrew Robson was appointed to run the day to day project activity in 2014. In mid-2015 Andrew left the project to take up a leadership role in agricultural remote sensing. Dr Karl Andersson replaced Andrew in March 2016, and with Mark Trotter's relocation to Central Queensland University, Karl also took over project management.

4.9 Pillar meetings

With the project's position in the Grazing Systems Management Pillar of the Feedbase Investment Plan (FIP), the project leader and research fellow attended and presented project updates at the pillar meetings when they were held each year. The meetings also included feedback sessions from representatives of the PRGs, and planning sessions for future participatory R&D projects.

The research fellows and project leaders also engaged directly with the PRGs, travelling to each location to meet and update each group. These meetings provided valuable feedback on the direction and application of existing and future research needs for growers.

In addition to the pillar meetings and PRG meetings, the research fellows and project leaders presented updates at the annual CRCSI conferences.

4.10 Participatory R&D

With the project run under the MLA's National Feedbase Investment Plan, a participatory research program was established with producer groups funded to work in collaboration with the researchers undertaking the core science. The Participatory Research Sites have provided a key point of partner engagement throughout the project. The PRS sites consist of a group leader (a consultant or government agent) and around 10-12 producer members. There were five PRS groups associated with this project that are based across southern Australia: Armidale New England (led by Lewis

Kahn); Central Victoria (Jim Shovelton); Hamilton Victoria (Peter Schroeder); Tasmania (Tony Butler) and Arthur River Western Australia (Alana Starkie).

The integration of producers into the research through the Participatory Research Sites (PRS) provided access to data from a range of pastures that would not have otherwise been obtainable. Five PRS were involved with the project, with approximately 12 producers with a lead consultant or government agent in each. The PRS engagement also provided the research team with a much broader view of the requirements of graziers from a variety of production systems, regions and climates across Australia. Important feedback included the need to focus on producer requirements (such as providing support for decision making at key times e.g. lambing, supplementary feeding), ensuring the sampling standards could be used by farmers in the field, improving on current practices, the need to be flexible to link with existing and future resources available to farmers. In addition to providing biomass data, the PRS groups provided critical feedback on the concept and the MDA.

In addition, NSW DPI were a crucial partner in the project, with Dr Robin Dobos providing input through insight on pasture management research and strategies, and management of the irrigation plots for some of the core research sites.

5 Discussion

5.1 Key research objectives

5.1.1 Evaluate the potential for Active Optical Sensors (AOS) to measure pasture biomass in the high rainfall zone of south-eastern Australia.

5.1.1.1 Suitability of the AOS for the estimation of pasture biomass

The principal motivation and objective for the project was to evaluate the potential for AOS to provide estimates (not measurements) of pasture biomass in the high rainfall zone of south-eastern Australia. The AOS referred to the sensors designed to detected changes in the amount of light reflected by plants. Lidar is also an AOS, but infers a height using the amount of time taken for an emitted pulse of light to return. The main measurement used from the AOS was the NDVI, firstly because it was the only reading available from the GreenSeeker, and subsequently because the different bands provided by the Crop Circle were not consistently any better at explaining the variation in GDM. The relationship between GDM and NDVI was not always robust, and from early the results mirrored those of previous research, e.g. Michalk and Herbert (1977); Freeman *et al.* (2007); Flynn *et al.* (2008); Redjadj *et al.* (2012); Schaefer and Lamb (2016), where pasture height was a vital component of the measurements. The use of the combined NDVIxheight or NDVI x log(height) index is key to the improved accuracy of modelled GDM estimates. Other research has found that using NDVI and height additively as individual inputs can be unsuccessful (Giepel and Korsaeth 2017), and here was not as well correlated with GDM as the combined index.

The main pastures where the NDVI was most useful was more commonly on lucerne and clovers more so than the grasses. The better fit to those pastures reflected two aspects. Firstly, the range in height was often narrow. Secondly, an upper canopy with a more open structure underneath resulted in an inconsistent relationship between GDM and height. The ability of the AOS to inform calibrations for GDM estimates was most clearly limited when the pastures were relatively uniformly fertile and actively growing with little senescent material, and any bare ground contributed to a high NDVI. This combination occurred during the main growing season in the phalaris and perennial ryegrass pastures in Victoria. Even when strong correlations were derived from the NDVI, the AOS is of limited use as values approach and exceed 0.80, and GDM exceeds 2500 – 3000 kg/ha. At these levels, the leaf area index approaches 3 and the AOS is not able to detect additional biomass under the upper leaves and the response ‘saturates’ (Weiser *et al.* 1986; Serrano *et al.* 2000; Liu *et al.* 2012).

Where the AOS was not sensitive to biomass in the phalaris and perennial ryegrass pastures during the main growing season in Victoria, plant height was a good determinant of GDM. This applicability of height to GDM calibrations was more so than in the other regions where the height measurements were influenced by standing senescent material. In contrast, the more variable pastures containing moderate amounts of senescent material resulted in a greater range of NDVI readings obtained from the grass-based pastured in NSW and Tasmania. This greater range contributed to the ability of the NDVI to discriminate variability in GDM.

The effect of senescent material on the ability for NDVI to inform GDM calibrations was both positive and negative in different circumstances. The positive influence was most clearly seen in the phalaris and perennial ryegrass pasture in Victoria, where it was not significant for autumn to spring (low senescent component), but was included in the summer calibration. However, too great a senescent fraction could hide the green fraction from the AOS, resulting in poor relationships. Just how much senescent material is useful for calibrations was not able to be identified conclusively here, because the method of cutting to ground included collecting litter, which during sorting was not easily distinguished from standing senescent material. By comparison, Trotter *et al.* (2012) found the correlation between an AOS and GDM was poor (in fact negatively correlated) for a sward with a green fraction of 15%, but was strongly correlated in the same pasture when the green fraction was 83% of the sward.

The combination of NDVI with height into a single index (Freeman *et al.* 2007; Schaefer and Lamb 2016) generally overcome the limitations of each being used separately. Where senescent material contributed to the apparent height measured by the plate meter, the height was penalised by a lower NDVI than would be measured for a high GDM% sward. Conversely, where the NDVI was saturated, the height measure incorporated further increases in biomass.

5.1.1.2 Pasture quality

The relationship between NDVI and pasture quality was only based on a low number of samples in one species (phalaris). The correlations for CP, digestibility, ME, ADF and NDF results were better than results reported elsewhere for NDVI (Starks *et al.* 2004), and comparable (Pullanagari *et al.* 2012a; Pullanagari *et al.* 2012b) or better (Zhao *et al.* 2007) than relationships found for multispectral reflectance. The relatively strong relationships perhaps reflect the small number of samples tested on the same paddock, but the pilot study suggests that the AOS could offer additional information to users.

5.1.1.3 Comparison of the measured and estimated green dry matter

Overall, the GDM estimated by the field team in Victoria (Jim Shovelton, Ian Gamble and Chris Blore) was well correlated with GDM, though there was substantial variability. The overall good correlation likely reflects the fact that height was the main determinant of GDM. In contrast, where NDVI was an important input to the calibrations in Tasmania, the estimates (either using the MLA pasture meter for perennial ryegrass or eyeball estimates for clover), the correlation between estimated and actual was substantially poorer. Given the generally strong correlations between GDM and measured height and NDVI in individual campaigns, the AOS offer the opportunity to calibrate users' eyeball estimates when generating self-calibrations.

5.1.1.4 Comparison of the Crop Circle with the GreenSeeker

While 2 and 3 band combinations from the Crop Circle could be superior to the simple NDVI from the Greenseeker, the fact that the particular best model varied between campaigns led to the decision to continue with just the one AOS after the first year. Due to the ease of use and cost, the GreenSeeker was sued to collect NDVI for the remainder of the project. This decision was not a judgement on the quality of the instruments, indeed as has been found previously both sensors have potential for agronomic application (Shaver *et al.* 2011).

5.1.1.5 Understanding error in sampling and its implications for data analysis

The differences in GDM and TDM observed with the comparative quadrat cuts pointed to substantial errors at source. When reviewing site photos of those comparison cuts, it was observable that some biomass was left behind. The data shows that 1 g of green biomass contains approximately 20% dry matter, so 5 g of moist pasture would be required to cause this 1 g of dry. Five g should not really be left behind, but it is an additive error process. Sorting errors in the lab (loss, mis-sorting green and senescent, difference in definition of what constitutes green and senescent biomass between operators) also add to potential errors. Combined, error due to sampling of around 10-20% is possible. This potential source of procedural error highlights the importance of adhering to protocol. The smaller the quadrat, the easier it should be collect all the biomass, however the inverse nature of what it represents per hectare means that it is also more important to minimise scale errors in the hundreds of kg/ha.

The potential for small amounts of biomass left behind points to a positive in the method of cutting to ground. Alternative methods that leave 1, 2 or 3 cm of pasture inherently risk a substantial variability in biomass measurements. On the flip side, cutting to ground as done in this project opens up two problems: 1. including soil in the sample which much be removed when sorting to prevent errors in calculation; and 2. Difficulty in sampling in moist conditions. Indeed, both of these were factors in the culling of a number of samples from the analysis. Both methods are practiced in the industry; what is important is an understanding of the benefits and otherwise of the chosen method, and adhering carefully to the protocol.

5.1.2 Develop a series of regional, seasonal and species specific calibrations that can be used by graziers to measure biomass using AOS for six key pastures types: ryegrass, fescue, phalaris, sub-clover, cocksfoot and lucerne.

The work conducted in conjunction with the PRGs provided data across the six key pasture types. Calibrations were derived for various regional/seasonal/species groups based on the NDVI, plate meter height, or the combined NDVI x height index. We established that it was appropriate to provide different calibrations for the different pasture types (perennial grasses, clover and lucerne), but not necessary to keep the grasses separate, simplifying the choice for a user (Giepel and Korsaeth 2017). Different seasonal calibrations differences were established for some situations where the relationship between GDM and the NDVI or height differed between early and late season, generally when height became more descriptive of GDM as the NDVI became saturated, though in established pastures in the NET year-round calibrations were derived. Other research has found that calibrations for biomass estimates are suited to certain periods or seasons, e.g. Teal *et al.* (2006) and (Trotter *et al.* 2012) though others have found consistent calibrations are suitable when stratified by the moisture content in the pasture (Serrano *et al.* 2016).

Regional calibrations have been loaded into the MDA for:

- Northern Tablelands, temperate grasses, year round
- Northern Tablelands, clover, year round
- Northern Tablelands, lucerne, year round
- Northern slopes NSW, tall fescue, autumn to spring
- Northern slopes NSW, lucerne, winter to spring
- North central and south western Victoria, phalaris and ryegrass, autumn to spring
- North central and south western Victoria, phalaris and ryegrass, summer
- Midlands Tasmania, perennial ryegrass, autumn to winter
- Midlands Tasmania, perennial ryegrass, spring

- Midlands Tasmania, clover, autumn to spring.

Custom calibrations for sites with lo sample numbers (< 40) are also loaded for:

- Northern slopes NSW, lucerne, summer
- Central west NSW, mixed pastures, winter
- Central west NSW, mixed pastures, spring
- Western Australia (Narrogin-Katanning), clover, winter
- Western Australia (Narrogin-Katanning), clover, spring
- Western Australia (Narrogin-Katanning), perennial ryegrass, winter to spring.

Alternative custom calibrations are also loaded as options for some of the regional calibrations where the NDVI or height alone provided satisfactory models:

- Northern Tablelands, clover, year round (NDVI only)
- Northern Tablelands, clover, year round (height only)
- Midlands Tasmania, perennial ryegrass, spring (height only)
- Midlands Tasmania, clover, autumn to spring (NDVI only)
- Midlands Tasmania, clover, autumn to spring (height only).

5.1.3 Develop a Mobile Device Application supporting the use of AOS as a real-time biomass estimation tool integrating the regional, seasonal and species calibrations and incorporating a simple self-calibration process to allow red meat producers to develop their own location specific calibrations.

5.1.3.1 Real-time biomass estimation

The MDA and integrated server developed by the UC Hitlab allows real-time estimation of pasture biomass using inputs from the Greenseeker and pasture height. The MDA interacts with a server hosted data base to provide updateable calibrations for the species, regions and seasons noted in section 5.1.2. The MDA also hosts customised calibrations developed through the self-calibration protocol.

The MDA allows for general one off biomass estimates, or a farm can be set up with a number of paddocks customised for the different species present. After entering the paddock details, the feed estimates can be saved.

Two aspects regarding using the calibrations provided need the users' attention. Firstly, the GreenSeeker. This AOS has a hotspot in its footprint (an oval with axes approximately 30 cm x 60 cm from 1 m above) which can bias a measurement. Users should be careful to avoid targeting the centre of the footprint over a plant, or bare ground, that is not representative of the footprint as a whole. Secondly, the pasture height. The plate meter used here is commonly used to easily collect a standard height, overcoming the possible subjectivity of selecting the height of individual leaves. However, the plate meter can give erroneous results if a few strong stalks support the weight of the plate resulting in a 'false' high. Unreliable measurements may also result on ground that is uneven due to e.g. pugging, cracks or erosion, particularly at low pasture heights (Redjadj *et al.* 2012).

5.1.3.2 Self-calibration

The self-calibration procedure in the MDA enables producers and industry experts to collect their own data and create their own calibrations. Users can generate self-calibrations based on the full procedure of taking pasture cuts, or by using their own eyeball estimates. As can be seen with some reasonably accurate eyeball estimates here (section 4.4), producers can be trained to provide quite accurate estimates (Edwards *et al.* 2011; Redjadj *et al.* 2012). The data from the campaigns collected during the project provides a rule of thumb for generating calibrations: the range in NDVI, height and GDM should be at least 0.2 units, 5 cm and 1000 kg/ha.

Using the MDA to quickly develop accurate eyeball-based calibrations can allow a grazier to easily transfer their skill to an untrained employee to collect objective feed estimates around the farm. This effectively transfers the experienced user's skill, freeing up valuable time as well as enabling consistent estimates to be made by different users. A lack of consistency is a major limitation to generating reliable data around a farm when done by different people (Redjadj *et al.* 2012).

The MDA contains training materials on how to use the feed estimate and self-calibration features. These materials are also included in Appendix **Error! Reference source not found.**.

5.1.3.3 Further development and recommended linkages

The MDA on as at end of project is provided only for Android platforms. In order to provide the service to as many users as possible, the delivery of the MDA is to be broadened to include iOS. As part of this redevelopment, several features are to be re-worked, including refining the navigation, enabling multi-user and consultant type access to records, and enabling export of feed estimate data to external software to support other systems a user may operate. Links via application programming interface (API) will facilitate the integration of the MDA data into farm management systems e.g. pasture yield mapping, and herd management systems.

5.2 Additional objectives

5.2.1 Train one PhD student and one post-doctoral fellow.

One PhD candidate (Paul Goodhue) was enrolled at the University of Canterbury, New Zealand, under the supervision of the original project leader (Dr Mark Trotter) and Dr Femke Reitsme. Paul was researching crowd-sourcing. In addition, one student (Morgan Chau) has enrolled (part-time) researching the application of a lidar unit to collect pasture height.

Two post-doctoral fellows were trained during the project. One (Dr Andrew Robson) moved on to take up a senior position at UNE in agricultural remote sensing. The second (Dr Karl Andersson) commenced for the last 1 ½ years of the project, including taking over as project leader when Cr Mark Trotter moved to Central Queensland University.

5.2.2 Pillar meetings and membership —.

The project leader and research fellow attended and presented project updates at the Feedbase Investment Plan meetings when they were held each year. The meetings included frank feedback sessions from representatives of the PRGs, and planning sessions for future participatory R&D projects. The research fellows and project leaders also engaged directly with the PRGs, travelling to each location to meet and update each group. This direct engagement encouraged continued interest and awareness, and feedback from the participants ensured that this project and ideas for future research is focussed on growers' needs.

5.2.3 Participatory R&D

This project was run under the MLA's National Feedbase Investment Plan. As part of this plan a participatory research program was established in which producer groups applied for funding to work in collaboration with the researchers undertaking the core science. Each site is funded for up to $20,000 per year. This project had five groups associated with it (from 15 applications) representing an additional investment by MLA of up to $300,000 over its term. Each PRS consists of approximately 12 producers with a lead consultant or government agent.

This participatory approach was a great feature of the project. Not only did it provide access to data from a range of pastures that would not have been otherwise easily obtained, is also provided the research team with a broad view of the requirements of graziers from a variety of production systems, regions and climates across Australia.

6 Conclusions/recommendations

6.1 Maintain the MDA

Resources should be provided to maintain the integrity of the database and MDA into the future. This maintenance will ensure technological changes are incorporated in the MDA so it doesn't become stranded. Linking the MDA to other farm management MDAs is also advisable. We are currently in discussion with linking the output to the Sheep CRCs AskBill MDA; further synergies are possible.

Management of the database is also vital to ensure that self-calibration data is legitimate. Periodic assessment of the data can then develop crowd-sourced calibrations, extending the coverage of regional, seasonal and pasture types beyond the current calibrations. Extending the range of calibrations can be efficiently achieved by linking with research projects. There are already two research projects investigating how the technology suits their purposes. These projects are focussed on the mixed farming zones in NSW, South Australia and Western Australia, and a grazing system on King Island. It would be beneficial for MLA to support engagement with research projects, in terms of matching protocols for data collection and analysis. This engagement is the most promising avenue for crowd-sourced calibrations.

Further, as the measurements from different GreenSeekers may vary, users need to be able to contact the Biomass team to organise an offset for to confidently use the generic calibrations in 'feed estimate'. This is not necessary for those users who wish to use their own self-calibrations, as they will be internally consistent. However it would still be advisable for those users to check for any drift or effect of accumulated grime and scratches on the unit.

6.2 Investigate engineering solutions for height measurement

The height measurements need to be collected manually with the plate meter. A better solution would be to have automatic detection of pasture height to greatly increase the efficiency of the process (Pittman *et al.* 2015). The instrument to provide height measurements would ideally be more accurate than the ±4.6 to ±7.2 cm (Scotford and Miller 2004) or ±3 cm (Schaefer and Lamb 2016). Ideally, the height sensor using the red and NIR bands enabling a single unit measuring height and NDVI, simplifying data collection. A validation exercise would then be required to match the data to the different footprint.

A Masters student at UNE is researching how a relatively cheap ($100) lidar sensors can be adapted to estimate pasture biomass. Assistance along these lines would feasibly involve vehicle mounting to log and relay height directly into the MDA.

Another option is to use a photogrammetric approach whereby overlapping photos are taken by digital cameras are mounted on a UAV. Such an approach requires substantial fieldwork and processing but large areas can be covered efficiently (Smith *et al.* 2016). While accuracy can be a limitation, Shahbazi *et al.* (2015) were able to obtain vertical accuracy of 0.4 cm and 1.7 cm. the Precision Agricultue Research Group at UNE has recently obtained promising results in a tall fescue pasture, and such work should continue (Priyakant Sinha, pers. comm.).

6.3 Extension of the project to incorporate remote sensing data

Researchers and producers have expressed interest in the potential to integrate this system with existing and developing remote sensing systems. Remote sensing offers a synoptic view of the grazing landscape with regular data collected, though there is a trade-off between temporal resolution and spatial resolution, e.g. MODIS offers a weekly composite at 250 metre pixel size, Landsat8 offers a 16 day return at 30 metre pixel size. Rapid advances in the number of satellites collecting data available is seeing this resolution become finer with costs decreasing. Satellite-based NDVI data can have strong correlations with pasture biomass (Edirisinghe *et al.* 2011), though the challenge for these system is local calibration.

The protocol developed in this project offers the potential to locally calibrate remotely sensed imagery increasing the accuracy and usefulness of this data. The sensor and MDA combination also offer a tool that can be applied at any time, providing the real-time estimate of biomass required by producers when satellite data is not available (through cloud or as limited by flight-path). In-turn the satellite platforms allow producers a historical view of the pasture production of their property (once calibrated) and also a synoptic view of the property when available informing longer term decision making.

Satellite data and indeed UAV data, can also be used to better target representative zones or transects for the hand held sensor and MDA. Further work should investigate the calibration of remotely sensed data for estimates, and the integration into site selection for sampling.

6.4 Extension of the project to integrate planner pasture quality, fodder budgeting, stocking rate calculator, and paddock rotation

The value in measuring pasture biomass is captured through applying this information to livestock stocking rates, either on a long term strategic basis or as day-to-day rotations. There is an opportunity to integrate the biomass MDA with other decision making platforms available. There are numerous companies with several different offerings, all of which have specific applications and end users in mind. MLA itself offers several stocking rate and fodder budgeting tools and web-applications which will also prove useful.

7 Key messages

The project has provided a range of calibrations for graziers to obtain objective estimates of pasture green dry matter.

The AOS by themselves were suitable for GDM estimation. Height measurements frequently improved the calibrations.

The Biomass MDA is a self-contained system that provides real-time, objective estimates of GDM, and facilitates users developing their own calibrations based on pasture cuts or on eyeball estimates.

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