Predicting accurate paddock-average pasture cover in Waikato dairy farms using satellite images

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Abstract

Effective monitoring of pasture cover on a regular basis is essential if dairy farmers are to increase profitability by making better pasture management decisions. We present results of a 2-year study on the use of satellite imagery to estimate pasture cover on dairy farms in the Waikato region. Data collection concentrated on the critical time for dairy farm pasture management between June and December. Two distinct relationships between the remotely-sensed normalised difference vegetation index (NDVI) and pasture cover were observed, with an inflexion point in the relationship at NDVI = 0.74. A two-part exponential model was fitted to the data, allowing the prediction error to be minimised both above and below the inflexion point. Model development showed that an algorithm based on NDVI and time-of-year accounted for approximately 80% of the variability in pasture cover measured within paddocks. The validation studies show that pasture cover was estimated with an error of prediction of approximately 10%, which equates to 260 kg DM/ha for a pasture cover range of 1500 to 3400 kg DM/ha. The accuracy demonstrated in this study has given the project's funders the confidence to explore a staged rollout of development, validation and commercial delivery, to make the technology available to all major dairy regions in New Zealand over the next 5 years.

Keywords: pasture cover, dairy, satellite imagery, rising plate meter, normalised difference vegetation index

Introduction

Efficient management of year-round systems based on grazed forages is seen as the key competitive advantage of the New Zealand dairy industry. It is well recognised that the ability to measure pasture quantity and utilisation will improve farmers' management capability and lead to further improvements in profitability and pastures and supplement utilisation. Fulkerson *et al.* (2005) predicted an increase in milk production of 8.9% from ryegrass based pastures as a result of improved allocation of feed to cows on a daily basis. Pasture measurement tools are available but not widely used in New Zealand with approximately 20% of dairy farms regularly using feed budgeting (Clark *et al.* 2006). Reasons include: lack of confidence in their accuracy (Li *et al.* 1998; Reeves *et al.* 1996; Stockdale 1984), high labour demand, and difficulty of use and cost (Lile *et al.* 2001). Consequently, neither the industry nor individuals have a reliable measurement of the quantity of pasture grown or utilised (Dairy Insight 2006).

In the Feed Production Strategy Report (Dairy Insight 2006), the authors have set challenging targets in the areas of 'feed utilisation' (increase feed utilisation across the industry to 85% of pasture grown by 2015) and 'objective measurement tools' (tools to measure quantity, quality and utilisation in use by 80% of farmers by 2015) in order to maintain New Zealand's competitive advantage in global markets. To meet these targets a major increase in the adoption of monitoring practices will be necessary, and having the correct tools is the first step to facilitate this change.

The 'Pastures from Space™' project in New Zealand has made advances in monitoring pasture cover in dairy farms using satellite imagery. The principle behind the project is simple; plants reflect incoming solar radiation differently in the red and the near infrared (NIR) parts of the electromagnetic spectrum. This difference in response can be used to create an index of plant greenness or Normalised Difference Vegetation Index (NDVI) (Tucker 1979), which represents the 'vigour' of plant greenness. While NDVI does not scale directly with vegetation biomass, it can be used to derive biomass if a systematic relationship can be described (Edirisinghe *et al.* 2000).

This paper reports on the development and validation of the 'Pastures from Space™' technology in New Zealand to develop a pasture cover prediction tool at the paddock scale for dairy farms.

Methods

A total of 22 satellite images and field measurements of pasture cover, were collected for the calibration and validation of the satellite-derived estimates. Field measurements were collected by Dexcel personnel from commercial (n = 8), research (n = 2) and corporate (n = 1) farms over 2 years (Year 1 = August 2005 - May 2006, 13 images; and Year 2 = June 2006 - December 2006, 9 images) in the Waikato region of New Zealand (Table 1). The farms were classified into geographic zones for the purpose of the statistical analysis (Fig. 1).

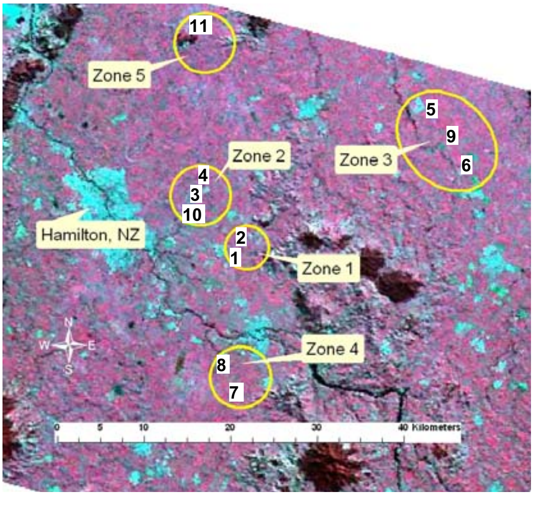
Up to a maximum of eight farms were sampled for

Table 1 Schedule of image acquisitions from SPOT-4 or SPOT-5 satellites and ground data collection for the last image in Year 1 and all images in Year 2, the number of farms sampled on each date and satellite details.

Collection Year	Sampling number	Image date (2006)	Pasture sampling dates (2006)	No. of farms sampled	Pixel size (m)	SPOT Satellite
1	S12	6 May	30 April – 1 May	7	10	5
2	S13	27 June	26 – 28 June	5	10	5
2	S14	16 July	14 – 20 July	6	10	5
2	S15	28 July	27 – 31 July	7	10	5
2	S16	9 August	10 – 11 August	6	20	4
2	S17	27 August	28 – 30 August	6	10	5
2	S18	14 September	15 – 18 September	8	20	4
2	S19	5 October	5 – 8 October	8	20	4
2	S20	9 November	9 – 11 November	5	20	4
2	S21	11 December	11 – 14 December	8	20	4

any image acquired, the number being limited by the size of the sampling team and the need to complete sampling within 4 days of image acquisition. The selection of farms to sample for any particular image date was determined by the following criteria: a) farms not affected by cloud cover, b) farms having sufficient paddocks available for sampling and to provide, as much as possible, a large range of pasture cover, and c) farms that minimised travelling time for sampling teams while maintaining a good distribution through the Waikato region.

Figure 1 Distribution of farms in the Waikato region and grouping into geographic zones for the collection and analysis of Year 2 data.



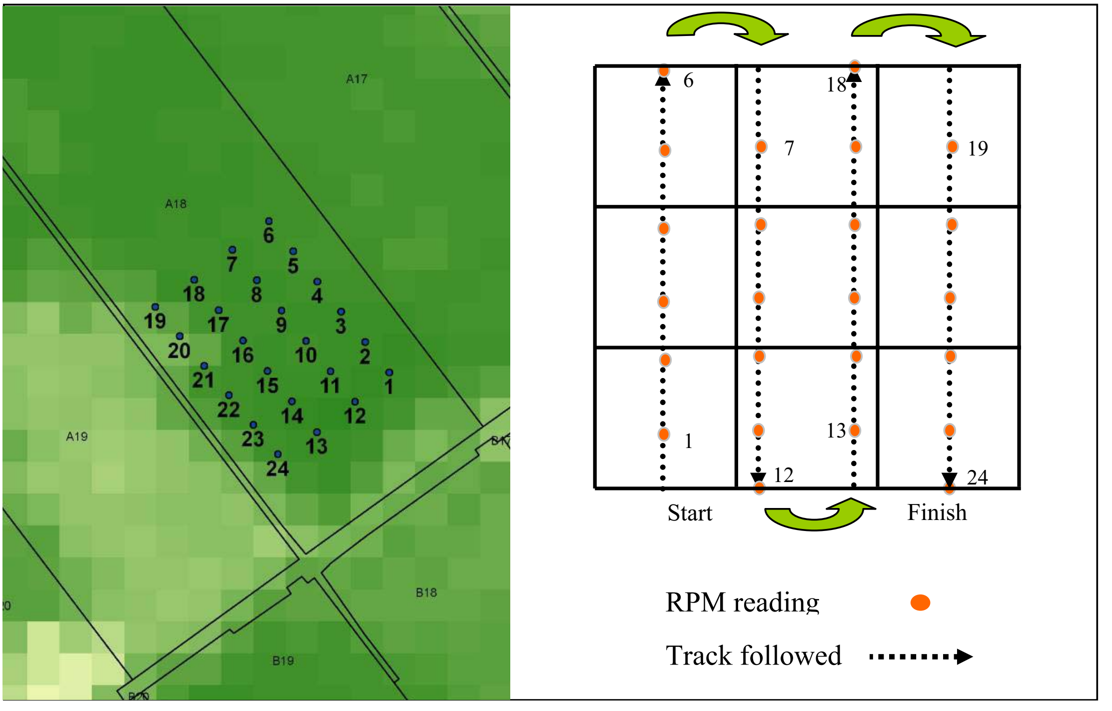
On average, five paddocks per farm and one grid per paddock were sampled to provide the maximum range of pasture cover estimates possible. Field estimates of pasture cover were collected using a rising plate meter (RPM) and by following pre-marked transects within a grid of 60 x 60 m^2 (Fig. 2) to provide understanding of spatial variability in pasture cover within and between paddocks on each farm (Clark *et al.* 2006). The RPM operator walked four transects of 60 m length and 15 m apart, taking an RPM reading every 1 m and recording the RPM value every 10 m. A total of 240 readings were collected as 24 x 10 m averages per grid. This equates to 10 readings per pixel for SPOT-5 images and 20 readings per pixel for SPOT-4 images. The total number of readings per grid is much greater than the recommended 50-80 readings per paddock (Thomson *et al.* 1997) required to obtain acceptable accuracy and allowed us to derive the best possible relationship between field and satellite data at the pixel level. Conversion of the RPM height to pasture cover was carried out using the daily equations published by Dexcel Ltd (www.dexcel.co.nz). The path followed by the RPM operator was recorded using a global positioning unit (GPS) with a positional accuracy of ± 5 m, to relate ground data to the corresponding pixel in the satellite image.

Satellite images were acquired from SPOT-4 (pixel size 20 m) and SPOT-5 satellites (pixel size of 10 m) (www.spotimage.fr). All images were processed using standard remote sensing procedures (Edirisinghe *et al.* 2000) before calculating the NDVI values for each image (Tucker 1979). The grid average of pasture cover and NDVI data were calculated using ArcGIS (Version 9.1, ESRI). S-Plus statistical software was used for the statistical analysis of these data.

Model development

The goal of model development was to define the relationship between the satellite-derived NDVI and the ground measurements of pasture cover at the pixel level, for different times of the milking season in order to then predict paddock-average pasture cover from NDVI. The initial analysis of the NDVI-pasture cover relationship for each image showed that data collected in Year 1 were more variable than those collected in Year 2. Therefore, the NDVI pasture cover model was developed using data collected in Year 2 (between June and December 2006), and because data collected in May 2006 behaved

Figure 2 Schematic representation of a 60 x 60 m sampling grid showing transects walked (dotted line), RPM recorded per transect and per grid (orange dots) and a SPOT-5 image showing actual locations of the RPM averages (blue dots) in relation to 10 m pixels.



like the Year 2 data these were also included in the model. Furthermore, the analysis of these data indicated that two distinct relationships between NDVI and pasture cover existed, with a point of inflection at about NDVI = 0.74. Although a model with a single equation covering the full NDVI range was investigated, the increased variability of pasture cover observed with NDVI > 0.74 increased the prediction error for NDVI < 0.74. Due to increased variation in pasture cover for increasing NDVI, the models were fitted on logarithmically (base 10) transformed data. Model 1 was fitted to NDVI < 0.74 based on the following equation:

$$\text{Pasture cover} \sim \text{NDVI} + \text{TIME} + \text{ZONE} + (\text{NDVI} \times \text{TIME}) + (\text{NDVI} \times \text{ZONE})$$

Where TIME is the image sample number (Table 1) and ZONE is the farm classification which groups farms spatially to investigate possible geographical differences contributing to the data variability (Fig. 1). Model 1 was further simplified by grouping individual dates into "PERIODS" as follows: Period-1 = June & July, Period-2= August, Period-3 = September & October, Period-4 = November & December and Period-5=May. Model 2 was developed by fitting a simple linear regression to NDVI > 0.74.

Finally, to simplify the application of the model, the following equation was fitted to each PERIOD, maintaining the fitted equations from the two models in a statistically continuous way. Specific coefficients (a, b and c) were determined for the individual periods so that the model captured the progress of the season from winter to summer. The final model allowed the prediction error to be minimised both above and below the inflection point.

$$\text{Pasture cover} = \exp\{a + b * \text{NDVI} + c * [\text{NDVI} - 0.74]\}$$

Model validation

For the last six data collections in Year 2 (August (S16) to December (S21), Table 1), two additional datasets from a commercial and a research farm were provided by Dexcel for validation. Paddock average pasture cover values were collected using a RPM from all paddocks on these two farms according to recommended industry practice (50-80 readings per paddock, Thomson *et al.* 1997). On three occasions there was no time difference between the collection of the ground data and the day of image acquisition, and these dates were used for the validation. The three images were acquired from the SPOT-4 satellite. A linear regression model was fitted between the satellite-predicted and the measured pasture cover, and the residual standard deviation and RSE were used as a measure of accuracy of the herbage mass estimation methods.

For the remaining three dates the time difference between ground data collection and image acquisition was between 5 and 7 days. These datasets were excluded from the analysis to minimise the introduction of additional errors.

Results and Discussion

Model 1 analysis

A total of nine images were collected in Year 2, with five from SPOT-4 and four from SPOT-5 satellites and on average six farms per image were sampled to provide ground data for comparison with satellite estimates of pasture cover (Table 1).

The analysis of the ground data showed that there was a large effect of time-of-year, with higher pasture cover for a given value of NDVI as the year progressed from winter to summer. For NDVI ≤ 0.74 there was also a strong, approximately linear, relationship between pasture cover and NDVI. For NDVI > 0.74 the variation in pasture cover values was larger than that for NDVI ≤ 0.74.

Analysis of the fitted model 1 for the data with NDVI ≤ 0.74 showed that NDVI, TIME, and the TIME x ZONE interaction contributed significantly ($P<0.01$) to the explanation of the data. NDVI alone accounted for only 18.3% of the variance for NDVI ≤ 0.74 while the inclusions in the model of a term for TIME explained an additional 63%. Consistent with previous results for data collected in Year 1 (Clark *et al.* 2006). The significance of the interaction indicated that the effect of ZONE changes with time.

The analysis of variance of the simplified model 1 showed that NDVI, PERIOD, ZONE, (PERIOD x ZONE) and (PERIOD x NDVI) contributed significantly to explaining the data variance (Table 2). ZONE was excluded from the model because it only explained an additional 0.5% of the variance and as a result the interaction between PERIOD and NDVI was no longer significant.

The error analysis for data from Year 2 showed that the standard error of prediction at the pixel level was 12% with a 95% confidence limit of 24%, which equates to a residual standard error (RSE) of 240 kg DM/ha at the midpoint (2000 kg DM/ha) in the range of 1000 – 3000 kg DM/ha.

Model 2 analysis

Significant increases in variance of pasture cover were observed for Period-1, Period-2 and Period-3 but not for Period-4, and therefore there was no need to fit the additional curve for NDVI > 0.74. The standard error of prediction at the pixel level for NDVI > 0.74 was 18% with a 95% confidence limit of 36%, which equates to a RSE of 522 kg DM/ha at the midpoint (2900 kg DM/ha) in the range 1800 to 4000 kg DM/ha.

Table 2 The significance and the percentage of variance in pasture cover accounted for by fitting normalised difference vegetation index (NDVI) and adding Period or Period + Zone (model 1) for data with NDVI ≤ 0.74.

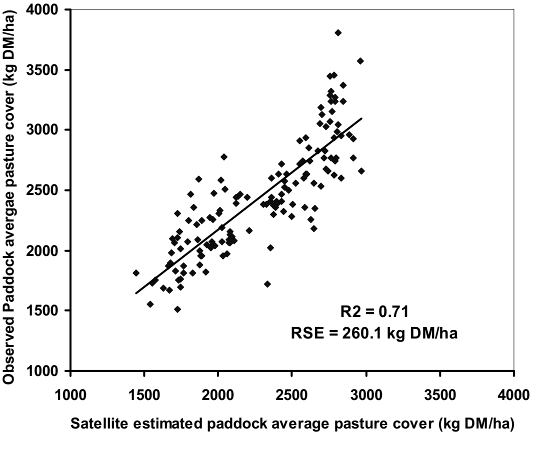
Model including:	Significance	Variance accounted for (%)
NDVI	<0.001	18.3
NDVI + Period	<0.001	80.9
NDVI + Period + Zone	0.047	81.4

Of practical importance to the producer is the standard error (SE) of prediction 'for the whole paddock', which is calculated as 'SE (paddock) = SE (pixel)/√N', where N is the number of pixels within the boundary of the paddock. As the number of pixels within the paddock increases, the SE decreases. Using SPOT-4 images (20 m pixels) provided satisfactory levels of accuracy in the prediction of paddock level pasture cover; using SPOT-5 images with 10 m pixels would reduce the prediction error. A one hectare paddock contains 25 SPOT-4 pixels or 100 SPOT-5 pixels.

Validation analysis

In the validation study the satellite estimates of paddock-average pasture cover were highly correlated with the paddock average pasture cover derived from RPM, measured on two commercial farms at three separate sampling periods. The coefficient of determination (r^2) and RSE for the individual farms and times of sampling

Figure 3 Relationship between the satellite-predicted and field-observed pasture cover for two farms and across three sampling dates.



ranged from 0.44 to 0.75 and 91.4 to 415.3 kg DM/ha, respectively. When combining the data across time and farms, r^2 was 0.71 with a RSE of 260.1 kg DM/ha for a pasture cover range of 1513 to 3457 kg DM/ha (Fig. 3). This RSE gives a prediction error of approximately 10.5% at the mid-point of the pasture cover range.

The estimates of accuracy for the satellite-predicted pasture cover compare well with other estimated errors (L'Huillier & Thomson 1988; Stockdale 1984) in New Zealand (average = 410 kg DM/ha; range 311-610 kg DM/ha) and in Australia (pre-grazing 534 kg DM/ha; post-grazing 479 kg DM/ha). The predictions covered the full range of pasture covers observed from rotationally grazed paddocks on commercial farms in the Waikato during winter and spring (1000 – 3400 kg DM/ha).

Conclusions

The model described is able to estimate the paddock-average pasture cover accurately on dairy farms in the Waikato region from satellite images. The error associated with the estimate is approximately 10% of the pasture cover value, which for the validation study equated to 260 kg DM/ha for a pasture cover range of 1500 to 3400 kg DM/ha. The project is now approaching the stage of delivering a 'pasture cover prediction tool' that will meet the characteristics specified by the Feed Production Strategy Group, i.e. 'A tool that delivers information in real time, is low cost, farmer-friendly and which will enhance the producer's ability to integrate detailed pasture production information into tactical and operational decision-making'.

Practical implications of conclusions

These results demonstrate that the technology is ready to move to the stage of pilot commercial delivery and this will be assessed in the Waikato from late winter 2007. In addition, research will commence in Canterbury to develop and validate a model specific to that region. Funders supporting this project have requested a 5-year plan to make the technology available to the majority of dairy farmers in New Zealand and to include sheep and beef properties.

Cloud cover remains a constraint to acquiring weekly images for New Zealand's major dairying regions even though per month each satellite has the potential to revisit a target area 13 times, providing a total of 26 potential looks over 21 days. Where an image is unavailable for a particular farm or district it will be possible to estimate cover based on the previous images' pasture cover together with an estimate of current pasture growth, to maintain frequent delivery of information to the producer. The length of time that such an extrapolation can be applied will depend on the time of year and the rate of pasture growth. The faster the growth, the shorter the period between successive images needed in order to minimise the introduction of growth rate prediction errors. However, projections of pasture cover data 7 to 14 days forward should be possible for maintaining good accuracy. Current pasture growth could be predicted from real time weather information in conjunction with a pasture growth model or estimated from historical data. These options are currently being investigated. The timeliness of data delivery to producers in an operational system is expected to be less than 72 hours from image acquisition. In pilot trials to date, the delivery time in the form of an email has ranged between 30 and 75 hours after image acquisition.

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