

Remote sensing of pasture quality

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Abstract. Farmers are aware of the importance of producing high quality pasture as it improves the animal performance and farm profitability. Typically, pasture quality is estimated by laboratory analytical techniques but these have limitations in terms of being time consuming, costly and requiring destructive sampling techniques in the field. To address these issues, remote sensing techniques have been proposed as an alternative that can provide real-time accurate information about pasture quality for decision-making in pasture management.

Keywords: Pasture quality, remote sensing, pasture management.

Introduction

Worldwide, farming systems are undergoing significant changes due to economic, environmental and social drivers. Agribusinesses must increasingly deliver products specified in terms of safety, health and quality. Increasing constraints are being placed on them by the market, the community and by government to achieve a financial benefit within social and environmental limits (Dynes *et al.* 2003).

In order to meet these goals, producers must know the quantity and quality of the inputs into their feeding systems, be able to reliably predict the products and by-products being generated, and have the skills to be able to manage their business accordingly. Easy access to accurate and objective evaluation of forage is the first key component to meeting these objectives in livestock systems (Dynes *et al.* 2003) and remote sensing has considerable potential to be informative and cost-effective (Pullanagari *et al.* 2012b).

Pasture quality

The value of pasture is a function of its contribution to animal performance as well as a function of its contribution to environmental and ecological services (Holmes *et al.* 2007). In addition, pastoral value will be determined by both pasture quantity and quality. The relative importance of the pasture's contribution to animal and environmental performance and the relevance of measures of quantity and quality will depend on the nature and context of the farming system. For example,

intensive dairy farming may focus on dry matter intake and nitrogen content of pastures while more extensive farming systems may focus on available herbage and amount of bare ground as critical drivers. However, while pasture quantity can be relatively easily measured, pasture quality has typically been considered too hard, in other words – too expensive, too inaccurate and too slow. As a result, the full potential of many grassland-based farming systems may not have been realised and useful tools to meet future drivers of profitability and sustainability are missing.

Animal performance

The performance of a grazing animal is determined by how well the energy and nutrients consumed are being utilised for maintenance *and* production. Pastures fed *in situ* ideally supply all essential energy and nutrients for the grazing animal but additional conserved pastures and supplements may be required according to seasonal conditions or farm system type. The differences between farm systems and feeding objectives are important when considering the value of forage quality information.

Feeding value and nutritive value are terms commonly used to describe the quality or value of forage for animal production (Ulyatt 1973). Feeding value refers to animal production responses when feed available does not limit voluntary feed intake and is a function of voluntary feed intake and nutritive value. Nutritive value refers to the responses in animal production per unit of intake of total dry matter and is a function of digestibility

of nutrients and the efficiency with which the nutrients are used for maintenance or production. Frequently the availability of forage will limit voluntary feed intake in both extensive and intensive systems and pasture quality will be key to animal performance.

Nutritive value of pasture is estimated from the measurement of key chemical attributes. The typical and important chemical attributes used for assessing and reporting on feed quality are crude protein or nitrogen, fibre (ADF: acid detergent fibre and NDF: neutral detergent fibre), metabolisable energy (ME) and organic matter digestibility (OMD), in addition an extensive range of other macro and micro constituents are reported for specific forages and systems. The digestibility of a pasture is an estimate of the intake retained by the animal (CSIRO 1990). It is strongly influenced by plant physical and chemical composition. Key physical attributes of pastures that govern its digestibility include species, presence of seed heads, and proportion of green and dead material while its chemical attributes include proteins, structural and non-structural carbohydrates, water and minerals.

Pasture management

Pastures are typically managed in a way that manipulates the quantity and quality of pasture by controlling the frequency and intensity of grazing. Management is complex; farmers must balance multiple variables and drivers in a constantly changing environment where earlier decisions have short medium and long-term implications for animal and pasture performance. As farms intensify and farmers face increasing challenges, remote sensing has potential to provide critical information on pasture quantity and quality in near-real-time. The frequency with which farmers will require data on pasture quality and quantity will depend on the farm type and level of intensification. For example, intensive dairying systems may utilise twice weekly pasture quality data whereas an extensive farm managing erosion risk may only require annual data.

Fertiliser management

Pasture growth can be limited for a number of reasons due to environmental factors such as temperature and moisture availability, but it can also be limited by soil fertility. Management of fertiliser inputs (type, rate and timing) are critical decisions in many grassland farming systems. These decisions are commonly based on information from physically testing soil or foliage chemistry, however, this data is time consuming to obtain, expensive and suffers from issues of sampling such as consistency and representativeness. Remote sensing has potential to alleviate some of these issues. For example, spatial distribution maps of pasture quality may indirectly indicate the soil nutrient status enabling the use of maps to highlight the nutrient limited areas. For example, spatial information of protein levels of the pastures could indicate the soil nitrogen status allowing the implementation of variable rate or site-specific fertiliser management, with fertiliser applied according to the potential of the plant to respond, with potential to

reduce fertiliser and environmental costs. Variable rate application of fertiliser can significantly improve the economic output, with a 26% higher cash surplus, over blanket application of fertiliser in extensive hill country grazing systems (Murray and Yule 2007).

Environment and ecological services

The value of pasture quality estimates for environmental and ecological services will depend on the pastoral system, its sensitivity to animal nutrition requirements, and internal and external environmental pressures. Existing research utilises objective measurement for example, savannah ecosystems in the north-eastern part of South Africa are highly degraded because of the difficulties in managing the vegetation cover. As a result overgrazing and land degradation are on-going and emerging issues across wide areas. Spatial pasture quality information may assist in the management of these areas. These benefits may lead to better understanding of the contribution of different components of the vegetation; to landscape integrity, as nutrient source for animals and to the viability of a system and the role of animal grazing patterns to sustainability of the system.

Pasture quality also has strong influence on animal methane and nitrous oxide emissions. A study by Harper *et al.* (1999) revealed that cattle grazing poor quality pasture produced ~8 percent CH₄ from gross energy consumed, while cattle fed with highly digestible and good quality pasture produced ~2 percent CH₄. Global and national level remote sensing of pasture quality would assist in more accurate estimates of greenhouse gases emissions and enable calculations at farm or regional level. There has been some progress (Ausseil *et al.* 2011) but further development is required. With environmental services often difficult to value, the potential for remotely sensed data on grassland quality to continue to develop will likely only occur if opportunities emerge to develop specific solutions for issues or regions.

Sensing of pasture quality

Laboratory-based methods

There are a number of on-farm tools available to estimate the quantity of pasture available and these are used for feed budgeting, including the management of pasture utilisation. In contrast, the measurement of pasture quality attributes has been largely reliant on traditional 'wet' chemistry and laboratory-based NIRS (near infrared spectroscopy) analysis. The Association of Official Agricultural Chemists (AOAC) has approved laboratory based analytical methods as a standard approach for estimating pasture quality parameters and the laboratory-NIRS approach are also accepted as having an accuracy close to that of wet chemistry and the relative cost is very low (Fig. 1). Laboratory NIRS devices typically have very high spectral resolution and are able to be closely calibrated to the desired pasture quality characteristics determined by wet chemistry. These methods are constrained, however, by the

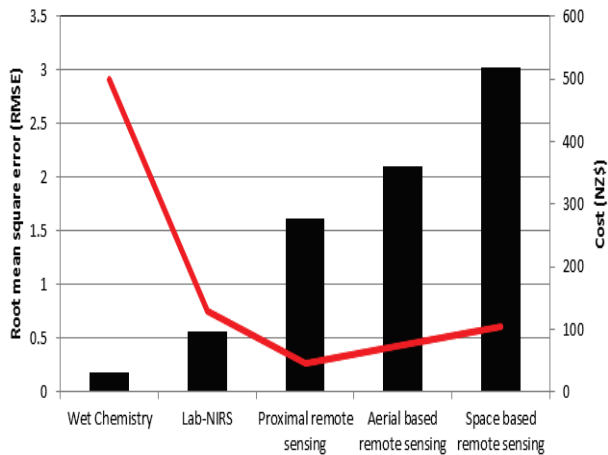


Figure 1. Accuracy (root mean square error: black columns) and cost (NZ\$: red line) of various methods to quantify crude protein content of pastures. Here 50 spatial random samples were considered in analysis to represent 1 hectare paddock variation. Results were computed from (Mutanga and Skidmore 2004; Knox *et al.* 2011; Pullanagari *et al.* 2012b)

destructive sampling required, the difficulty in getting “representative” samples, delays between sampling time and the results being available and the cost and the practicality of accessing sampling sites. No information on the spatial extent or distribution of pasture quality is readily available unless field sampling records the spatial details.

Proximal remote sensing

Extending laboratory NIRS techniques to the field, remote sensing technologies have been developed for real-time and non-destructive estimation of pasture quality. Proximal remote sensing is operated by hand or

mounted on a vehicle, these have great potential to predict pasture quality (Pullanagari *et al.* 2012b; Kawamura *et al.* 2009; Biewer *et al.* 2009) because of the high spectral resolution and negligible interference from atmospheric conditions affecting the data. Compared to wet-chemistry, the relative cost involved to determine crude protein content using proximal sensing is substantially reduced but the accuracy was lowered (Fig. 1). There are also significant sampling issues, with heterogeneous paddocks requiring large areas to be sampled.

Aerial and space-based remote sensing

As aerial and satellite-based remote sensing instrumentation has been refined, the ability to quantify vegetation characteristics has expanded to regional and national level. However, little research has been completed to quantify pasture quality parameters. In the early 1990s, NASA started examining the foliar biochemistry in forest landscapes using the airborne instrument High Resolution Imaging Spectrometer (HIRIS) (NASA 1994).

Today, several airborne instruments are operational. Knox *et al.* (2011) mapped forage nutrients (nitrogen and phosphorus) in Africa savannahs by using an airborne sensor (CAO Alpha sensor). Similarly Ramoelo *et al.* (2012) mapped canopy nitrogen at a regional level using the RapidEye sensor in the Kruger National Park (KNP), South Africa (Fig. 2). The relative direct cost to determine pasture quality is slightly higher than the proximal remote sensing (Fig. 1) but extensive area can be covered in a short time. The accuracy was relatively lower for space based remote sensing because of lower spectral and spatial resolution and the interference of atmosphere conditions.

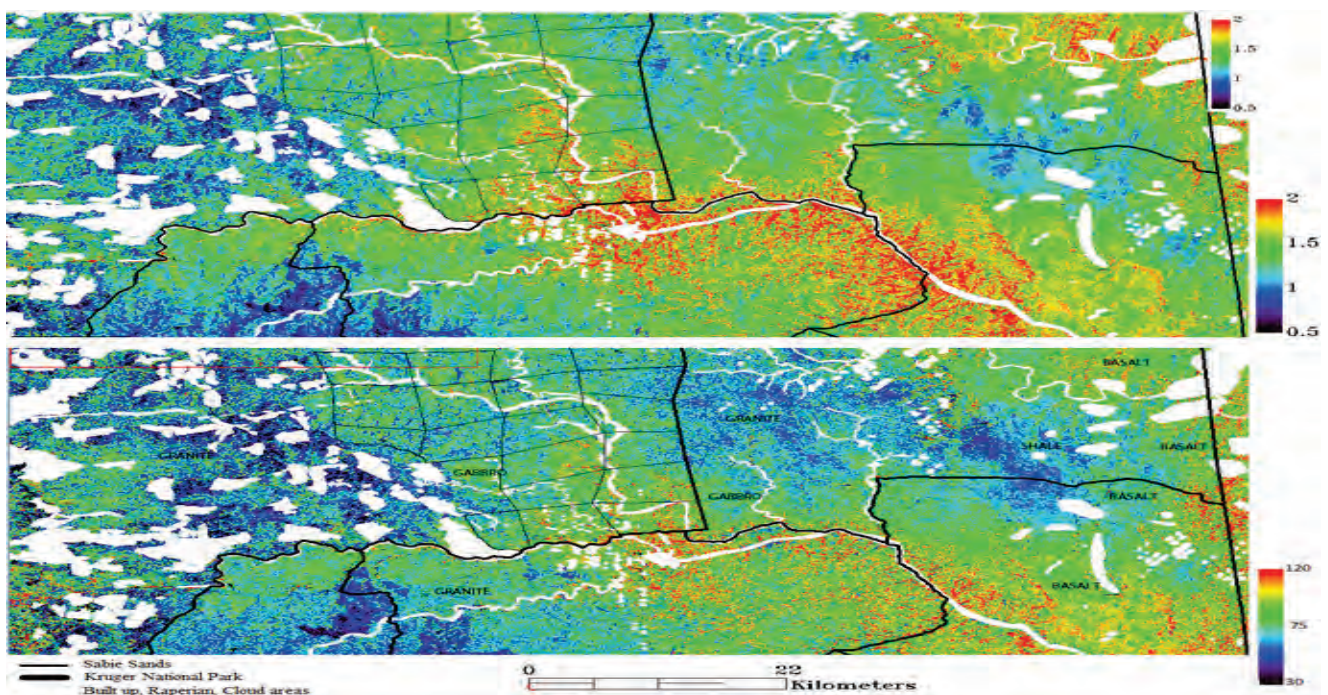


Figure 2. Foliar nitrogen concentration (% of dry matter) (Top) and canopy nitrogen (N× photosynthetic vegetation) (kg dry matter/ha) (Bottom) maps across a land use gradient in the savannah ecosystem ranging from communal lands, private game reserves (Sabi Sands) and Kruger National Park (Ramoelo *et al.* 2012).

Sensing technology – past and future

Since the first generation of remote sensing tools such as multispectral sensors became widely available, numerous studies have been conducted to assess vegetation features. However, their usefulness has been limited for qualitative and quantitative terms because of rather low spectral and spatial resolution. The sensors with low spectral resolution are unable to resolve the subtle spectral features caused by biochemical changes responsible for affecting pasture quality. Spatial resolutions less than the size of a paddock are needed to be of practical value in farm management. In particular, these early remote sensing systems cannot quantify pasture quality in grassland systems that exhibit a diverse natural and spatial heterogeneity (Pullanagari *et al.* 2012a). To quantify such complex grassland systems, high spatial and spectral resolution sensing systems are essential (Schellberg *et al.* 2008). The new remote sensing systems with capability of high spectral and spatial resolution have made it possible to derive more detailed information so that pasture quality can be quantified accurately.

As compared to air and space based remote sensing, proximal sensors have been widely used in research to establish methods to quantify herbage quality, due to their wide availability and relative ease of operation (Thulin *et al.* 2012). Selected studies in the literature demonstrating the potential for remote sensing to estimate pasture quality parameters of grasslands with their validation results are summarized in Table 1. In Table 1, most of the results are obtained from proximal

remote sensing studies, so useful estimates of pasture quality from remote sensing will require robust validation and error term which is appropriate for the quality parameter and farming system, for example extensive pastoral agriculture may have more tolerance for larger error in estimates than intensive pastoral and forage harvesting systems which require accurate estimates.

The next generation of remote sensing instruments (*e.g.* EnMAP, HypSI, Sentinel-2, WorldView-3 *etc.*) are expected to deliver technical advances in sensing at lower costs. This result leading to new opportunities for development of useful methods to deliver real-time, cost effective data for industry. The challenge will be to pair technology development with a value proposition which will see industry adoption of these technologies. Ramoelo *et al.* (2012) recently showed the potential of the commercial based RapidEye satellite sensor, with its high spatial and temporal resolution, to successfully map grass quality (leaf N) for larger spatial extents at a regional scale (Fig. 2). This study highlighted that the strategic placement of important bands such as the red edge in the development of new sensors enable estimation of grass quality over large areas. In addition, robust and sophisticated algorithms need to be further developed to improve the accuracy so, that the methods can be successfully applied for a wider variety of locations. For example, artificial neural networks (ANNs) can provide more accurate solutions than traditional statistical techniques, and are highly effective in a complex environment (Mas and Flores 2007).

Table 1. Reported accuracy in estimating pasture quality parameters.

Pasture quality parameters (% DM)	Range	Coefficient of determination (R ²)	Root mean square error (RMSE)	Remote sensing type	Grassland type	Reference
Crude protein	9.0-19.5	0.60	1.31	Proximal	Managed hill country pastures	(Kawamura <i>et al.</i> 2008)
	-	0.83	-	Proximal	Managed pastures	(Biewer <i>et al.</i> 2009)
	9.38-28.41	0.78	2.33	Proximal	Managed pastures	(Pullanagari <i>et al.</i> 2012b)
	4.39-30.45	0.62	2.77	Proximal	Managed pastures	(Thulin <i>et al.</i> 2012)
	-	0.87	2.9	Proximal	Managed grasslands	(Schut <i>et al.</i> 2006)
Nitrogen	0.53-1.44	0.48	0.12	Space borne	Rangelands	(Ramoelo <i>et al.</i> 2012)
	0.83-3.42	0.60	0.13	Space borne	Unmanaged rangelands	(Mutanga and Skidmore 2004)
	0.31-0.91	0.53	0.16	Air borne	Unmanaged rangelands	(Knox <i>et al.</i> 2011)
	0.83-3.42	0.80	0.27	Air borne	Unmanaged rangelands	(Skidmore <i>et al.</i> 2010)
Acid detergent fibre	25.2-41.0	0.65	2.15	Proximal	Managed pastures	(Kawamura <i>et al.</i> 2008)
	19.99-38.19	0.82	2.23	Proximal	Managed pastures	(Pullanagari <i>et al.</i> 2012b)
	-	0.79	12.4	Proximal	Managed grasslands	(Schut <i>et al.</i> 2006)
	-	0.50	-	Proximal	Managed pastures	(Biewer <i>et al.</i> 2009)
Neutral detergent fibre	41.00-67.6	0.37	4.15	Proximal	Managed pastures	(Kawamura <i>et al.</i> 2008)
	28.66-67.32	0.75	4.63	Proximal	Managed pastures	(Pullanagari <i>et al.</i> 2012b)
Metabolisable energy	8.51-13.16	0.83	0.46	Proximal	Managed pastures	(Pullanagari <i>et al.</i> 2012b)
	6.6-12.5	0.50	0.50	Proximal	Managed pastures	(Biewer <i>et al.</i> 2009)
Digestibility	44.99-85.56	0.62	4.85	Proximal	Managed pastures	(Thulin <i>et al.</i> 2012)

Challenges in adapting remote sensing technologies for pastoral agriculture

There have been some notable achievements from sensing research in agriculture. The “Pastures from Space” programme was developed by CSIRO and partners in Australia and it delivers near real-time pasture growth rate (PGR) and feed on offer (FOO) directly to the graziers for management of feed supply (Donald *et al.* 2010). The estimates are predicted based on MODIS derived normalized difference vegetation index (NDVI) in combination with soil and climate data and a light-use-efficiency model. Complementary pasture quality information is not yet available and constitutes an essential component of remotely sensed management of grazing systems.

In contrast to crops, pastures are more complex in nature since the quality and diversity will change over time due to invasive weeds, animal grazing and trampling, presence of many different species, changing stages of maturity and varying proportions of green and dead material. These complex interactions are one of the major constraints in adapting remote sensing technologies for pasture quality estimation.

Precision management of pasture quality requires information at a spatial scale that captures variability that influences production and economic return. For instance, Rahman *et al.* (2003) concluded that 6 m² pixels would be optimum for estimating biomass, photosynthesis and water content of southern California grassland and chaparral ecosystems. Similarly, Kawamura *et al.* (2009) also indicated that a sampling interval of 5 m² is essential to capture the maximum amount of variation for mapping biomass and nutrient content in hill country pastures. Such extents of spatial resolution can currently only be achieved through proximal and some commercial airborne (*e.g.* HyMap, AVIRIS, Carnegie Airborne Observatory (CAO) *etc.*) and space borne (*e.g.* Rapid Eye, WorldView-2) remote sensing systems.

High spectral resolution is crucial for quantifying pasture quality parameters as it enables the subtle spectral features mainly due to quality components to be identified, thus better correlation between remotely sensed data feed quality parameters can be expected and provides a solution to issues of non-representative sampling ideal resolution could be about 10 nm where subtle absorption features can still be explained (Mutanga and Skidmore 2004). Currently, most of the space borne multispectral sensors has broader spectral bandwidth resolution; hence they are not useful for quantifying pasture quality parameters accurately. For instance, GreenSeeker® (multispectral proximal sensor) has broad resolution bands obscures the fine spectral features that are relevant to quality parameters.

The return frequency of the sensor to record data for the same pasture also called temporal resolution is also another important element in remote sensing to enable monitoring of pasture quality. Generally pastures are highly variable and dynamic, not only spatially but temporally, as they are largely influenced by both physiological state and environmental conditions particularly moisture stress and temperature, all of which

change over time. The proportion of photosynthetically active (PV) to non-photosynthetically active (NPV) components in pastures changes over time, with proportion of dead material used as a tool to estimate pasture quality by industry (Beef + Lamb NZ 2012). In addition, continuous stocking and rotational grazing systems also influence the pasture quality characteristics. Data capture at regular-time intervals could enable effective monitoring of these changes and enable new levels of tactical planning on-farm.

Currently the availability of sensors with the desirable spatial, spectral and temporal features is limited. High quality data can be sourced from commercial sources but the data remains too expensive for extensive spatial coverage and there are significant temporal issues related to acquiring images, *e.g.* in NZ cloud cover limits the frequency that image can be acquired. Thus both cost and availability of images remain major limitations.

The accuracy of estimating pasture quality parameters is also influenced by the effect of leaf water content where high levels obscure the main spectral features of important biochemicals (Ramoelo *et al.* 2011). Several researchers have proposed different techniques to minimise the effect of leaf water content, however, the challenge to remove its effect completely remains.

Mapping pasture quality components such as nitrogen, phosphorus and fibre, using spectral data in combination with environmental variables has been shown to improve calibrations and predictions (Knox *et al.* 2012). Here the authors used slope, altitude, aspect, geology, geological classes, soil maps, fire, plant age and species as environmental variables to contribute to their models of pasture quality.

In addition to quantitative measurements, remote sensing enables the estimation of spatial distribution maps for each quality component. With access to this information, farmers and land managers can determine the value depending on farm type and challenges. For example for fencing or subdivision of paddocks for grazing, for application of fertiliser or for understanding animal feeding behavioural changes that shifts from optimal to sub-optimal pasture use both in conserved and communal areas. This type of information is very useful, and enables to achieve sustainable grazing which could minimize land degradation, especially in communal grazing areas.

Conclusion

Remote sensing has potential to provide pasture quality information, however further refinement in prediction accuracy of pasture quality (crude protein, fibre *etc.*) and instrumentation such as spectral, spatial and temporal resolutions is needed, and a challenging range of issues need to be resolved. In addition, challenges exist in analytical methodologies. However, the future availability of remote sensors and technologies better suited for accurate pasture quality analysis are expected to drive this technology forward by providing accurate solutions at low cost and high temporal coverage.

A successful sensing based estimation system of pasture quality, given the considerations above (high spatial, spectral and temporal resolutions), would have the following characteristics: a capacity to estimate a wide range of quality parameters, from remote sensing delivered at regular intervals at a cost and speed which optimises the value proposition for the industry.

References

- Ausseil AG, Dymond JR, Dynes R, Shepherd JD, DeVantier B, Sutherland A (2011) Estimating pasture quality using Landsat ETM+: application for the greenhouse gas inventory of New Zealand. In 'International Symposium on Remote Sensing for the Environment'. Sydney, Australia.
- Beef + Lamb NZ (2012) A guide to feed planning for sheep farmers First published by the New Zealand sheep council–1994 updated June 2012. <http://www.beeflambnz.com/Documents/Farm/A%20guide%20to%20feed%20planning%20for%20sheep%20farmers.pdf> Accessed 15 Dec 2012.
- Biewer S, Fricke T, Wachendorf M (2009) Development of Canopy Reflectance Models to Predict Forage Quality of Legume-Grass Mixtures. *Crop Science* **49**, 1917-1926.
- CSIRO (1990) Feeding standards for Australian livestock: Ruminants. Standing Committee on Agriculture and Resource Management Ruminant Subcommittee. (CSIRO Publishing: Melbourne).
- Donald G, Gherardi S, Edirisinghe A, Gittins S, Henry D, Mata G (2010) Using MODIS imagery, climate and soil data to estimate pasture growth rates on farms in the south-west of Western Australia. *Animal Production Science* **50**, 611-615.
- Dynes RA, Henry DA, Masters DG (2003). Characterising forages for ruminant feeding. *Asian-Australasian Journal of Animal Sciences* **16**(1), 116-123.
- Harper L, Denmead O, Freney J, Byers F (1999) Direct measurements of methane emissions from grazing and feedlot cattle. *Journal of Animal Science* **77**, 1392-1401.
- Holmes CW, Wilson GF, Mackenzie DDS, Flux DS, Brookes IM, Davey AWF (Ed. D Swain (2007) 'Milk production from pasture.' (Massey University: Palmerston North, New Zealand)
- Kawamura K, Betteridge K, Sanches ID, Tuohy MP, Costall D, Inoue, Y (2009) Field radiometer with canopy pasture probe as a potential tool to estimate and map pasture biomass and mineral components: a case study in the Lake Taupo catchment, New Zealand. *New Zealand Journal of Agricultural Research* **52**, 417-434.
- Kawamura K, Watanabe N, Sakanoue S, Inoue Y (2008) Estimating forage biomass and quality in a mixed sown pasture based on partial least squares regression with waveband selection. *Grassland Science* **54**, 131-145.
- Knox NM, Skidmore AK, Prins HHT, Asner GP, van der Werff HMA, de Boer WF, van der Waal C, de Knegt HJ, Kohi EM, Slotow R, Grant RC (2011) Dry season mapping of savanna forage quality, using the hyperspectral Carnegie Airborne Observatory sensor. *Remote Sensing of Environment* **115**, 1478-1488.
- Knox NM, Skidmore AK, Prins HHT, Heitkönig IMA, Slotow R, van der Waal C, de Boer WF (2012) Remote sensing of forage nutrients: Combining ecological and spectral absorption feature data. *ISPRS Journal of Photogrammetry and Remote Sensing* **72**, 27-35.
- Mas JF, Flores JJ (2007) The application of artificial neural networks to the analysis of remotely sensed data. *International Journal of Remote Sensing* **29**, 617-663.
- Murray RI, Yule IJ (2007) Developing variable rate application technology: Economic impact for farm owners and top-dressing operators. *New Zealand Journal of Agricultural Research* **50**, 65-72.
- Mutanga O, Skidmore AK (2004) Integrating imaging spectroscopy and neural networks to map grass quality in the Kruger National Park, South Africa. *Remote Sensing of Environment* **90**, 104-115.
- NASA. (1994). Accelerated Canopy Chemistry Program. In J. Aber (Ed.), Final Report to NASA-EOS-IWG. Washington, DC: National Aeronautics and Space Administration.
- Pullanagari RR, Yule IJ, Hedley MJ, Tuohy MP, Dynes RA, King WM (2012a) Multi-spectral radiometry to estimate pasture quality components. *Precision Agriculture* **13**, 442-456.
- Pullanagari RR, Yule IJ, Tuohy MP, Hedley MJ, Dynes RA, King WM (2012b) In-field hyperspectral proximal sensing for estimating quality parameters of mixed pasture. *Precision Agriculture* **13**, 351-369.
- Rahman AF, Gamon JA, Sims DA, Schmidts M (2003) Optimum pixel size for hyperspectral studies of ecosystem function in southern California chaparral and grassland. *Remote Sensing of Environment* **84**, 192-207.
- Ramoelo A, Skidmore AK, Cho MA, Schlerf M, Mathieu R, Heitkönig IMA (2012) Regional estimation of savanna grass nitrogen using the red-edge band of the spaceborne RapidEye sensor. *International Journal of Applied Earth Observation and Geoinformation* **19**, 151-162.
- Ramoelo A, Skidmore AK, Schlerf M, Mathieu R, Heitkönig IMA (2011) Water-removed spectra increase the retrieval accuracy when estimating savanna grass nitrogen and phosphorus concentrations. *ISPRS Journal of Photogrammetry and Remote Sensing* **66**, 408-417.
- Schellberg J, Hill MJ, Gerhards R, Rothmund M, Braun M (2008) Precision agriculture on grassland: Applications, perspectives and constraints. *European Journal of Agronomy* **29**, 59-71.
- Schut AGT, van der Heijden GWAM, Hoving I, Stienezen MWJ, van Evert FK, Meuleman J (2006) Imaging Spectroscopy for On-Farm Measurement of Grassland Yield and Quality. *Agronomy Journal* **98**, 1318-1325.
- Skidmore AK, Ferwerda JG, Mutanga O, Van Wieren SE, Peel M, Grant RC, Prins HHT, Balcik FB, Venus V (2010) Forage quality of savannas — Simultaneously mapping foliar protein and polyphenols for trees and grass using hyperspectral imagery. *Remote Sensing of Environment* **114**, 64-72.
- Thulin S, Hill MJ, Held A, Jones S, Woodgate P (2012) Hyperspectral determination of feed quality constituents in temperate pastures: Effect of processing methods on predictive relationships from partial least squares regression. *International Journal of Applied Earth Observation and Geoinformation* **19**, 322-334.
- Ulyatt M (1973) The feeding value of herbage. *Chemistry and biochemistry of herbage* **3**, 131-178.