Monitoring landscape changes using remote sensing technology in southern Africa

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Abstract. Rangelands are a major global resource, and there is an urgency to improve the assessment of landscape performance to capture carbon, produce biomass, and improve water use. Effective monitoring necessitates the collection of high quality rangeland condition data using repeatable techniques. Despite much effort, there are few comprehensive data sets that allow confident detection of landscape change. Data are lacking for several reasons, including high cost of data collection, conflicting methodologies, and loss of archival data. Satellite imagery provides the basis for trend and pattern analysis of rangeland in different conditions classes and this paper presents some examples of the analysis and interpretation of selected imagery from southern African rangelands. One approach to understanding rangeland change is to identify models that use functional concepts to describe landscape performance. Rangeland water use has being equated to that of more thirsty crops, resulting in further pressure to convert rangeland to dryland cultivation. Water use efficiency (WUE) is of considerable value in defining functionality. Here, WUE defines the ability of an ecosystem to produce above-ground biomass (kg DM) per unit of actual evapotranspiration (mm). It been calculated for several condition classes at sites in arid and semi-arid rangelands. In the past, estimates of WUE have been hampered by the scarcity of reliable net primary production (NPP) and evapotranspiration data. With the availability of spatially explicit estimates of actual evapotranspiration (ET_a) from the MODIS programme, it is now possible to validate annual ET_a surfaces at a spatial resolution of 1 km. We have validated these ET_a surfaces for southern Africa using a range of instruments and approaches. In addition, a global annual net primary production (MOD17) surface is available from MODIS. By combining these products, we have prepared an estimate of WUE (WUE=NPP/ ET_a) for natural rangelands in southern Africa for 2009. WUE varies spatially, with values ranging from 0.1 kg DM mm/ha/y in the arid western regions to >8 kg DM/mm/ha/y in the forests and grasslands of the eastern region. Using data from several ground-based measurements of WUE, this surface has been validated, and demonstrates that this is a useful product for comparing landscape management strategies and condition classes. I show how this product, and other remote sensing products, can be used to evaluate different land management strategies.

Keywords: Degradation, rangeland, remote sensing, MODIS, LAI, NPP.

Introduction

The monitoring of rangeland to assess changes in rangeland condition over time has been the subject of many research publications (Tueller 1991; Palmer and Fortescue 2004; Vanderpost *et al.* 2011; Bastin *et al.* 2012). Initially the techniques focussed on field-based measurements, but with the increase in availability of remote sensing products, there was an expectation that remote sensing would provide rapid and definitive answer to the challenges of detecting and monitoring rangeland degradation and associated changes in productivity (Brinkmann *et al.* 2011). With an almost exponential improvement in the resolution of imagery since the 1970's, and the enhanced visibility of objects and features such as trees, shrubs and patches, there was a belief that the real-time decision making would be possible. However, these expectations do not appear to have been realized, as with higher resolution came the challenges of data capture, archival and analysis. In addition, research supporting the interpretation of changes varies between pixel to pixel comparison (Palmer and van Rooyen 1998) with limited spatial perspectives, to multi-band analysis (Bastin *et al.* 2012).

Recently, there has been a surge in general interest to assess and improve the performance of landscapes to capture carbon, produce biomass for food and fibre, and improve water use (Grace *et al.* 2002; Grace 2004) and to provide the framework for payments for ecosystems services (Stringer *et al.* 2012). Effective assessment of global and local carbon stocks necessitates the collection of high quality field data using repeatable techniques (Ryan *et al.* 2011), and when coupled with modelling and remote sensing (Cabello *et al.* 2012), the likely result is an improved understanding of functional processes on rangeland. Despite generations of efforts to collect quality rangeland condition field data, there are still few comprehensive data sets that enable effective and confident detection of global landscape change. Most data are site specific and don't meet the requirements for regional or global assessments. Data relating to landscape condition and performance have been lacking for several reasons, including high cost of collecting field data (Kilpatrick *et al.* 2011), conflicting methodologies that prevent effective trend analysis, and loss of archival data. In this paper, I will describe some of the processes that drive rangeland change in southern Africa, and explore the suitability of several remote sensing products to parallel and further interpret these trends.

Degradation in southern African rangelands

In southern Africa, the degradation debate is polarised between those who see the rangeland condition on extensive freehold farms as the desired state, and those who regard the condition on collective livestock production in traditional villages as a justified modification to achieve legitimate livelihood objectives. The communal rangelands are concentrated in the former homeland areas of South Africa and areas under traditional land-use systems in Lesotho, Swaziland, Botswana and Namibia. In South Africa, the communal areas constitute about 13% of the land surface area but are home to 25% of the human population and hold about half of all livestock (Scogings *et al.* 1999). There are now rangelands that were historically commercial (freehold) farms that have recently been transferred to communal tenure as part of homeland consolidation or more recent (post 1994) land redistribute-ion. These recent changes in land-use provide an ideal opportunity to explore the impact of the change of land tenure on the rangeland resource. The third significant grazing resource available to communal farmers are the arable lands that are either abandoned (and thereby effectively a permanent extension of the range) or are still in use and become a common grazing resource after harvest, with crop residues providing grazing during the dry season. This phenomenon of using the cultivated lands as part of the grazing resource is prevalent in many areas under communal tenure but is particularly noticeable in countries such as Lesotho where there are no fences, and during the dry season herders actively focus the livestock grazing on these resources. In regions of South Africa such as the former Transkei and Ciskei (now part of the Eastern Cape), where there is an general absence of active herding, and poorly maintained fences, livestock wander freely onto both cultivated and abandoned areas and these areas represent a significant resource available to graziers in the dry season.

There is a long history of communal grazing within many of these areas as well as claims of associated land degradation. The first official reports of land degradation in the form of overgrazing and soil erosion were recorded during the 1880s in the Herschel district of Ciskei (Bundy 1988) and by the 1920s such reports were widespread in both the Ciskei and Transkei (Beinart 2003) where only common property tenure prevails. Ciskei and Transkei were regions where traditional communal tenure arrange-ments remained from before the pre-colonial era, and were later (post-1930) consolidated to form “homelands” during the apartheid era. Several studies report on components of land degradation on common property, including reduced productivity (Wessels *et al.* 2004), increased soil erosion (Kakembo and Rowntree 2003), change in the composition and basal cover of vegetation (Vetter *et al.* 2006; Anderson and Hoffman 2007; Todd and Hoffman 2009) and increases in woody shrubs (Shackleton and Gambiza 2008). This trend in degradation has been attributed to several drivers, including high livestock populations; an absence of con-ventional grazing management practices such as rotational grazing and resting; limited access to markets (Palmer *et al.* 1999); poverty (Meadows and Hoffman 2002); and that livestock populations are increasingly being maintained by external inputs which has a direct effect on secondary productivity (Vetter and Bond 2012).

General models of rangeland degradation suggest that soil and nutrients are lost and conversion of rainfall into primary productivity – rain use efficiency (RUE) - is diminished (Ludwig *et al.* 2004). These models are supported by case studies on ‘non-resilient' landscapes as well as ‘robust' or ’resilient' landscapes (Holm *et al.* 2003b). In the latter case, when rainfall was mostly average or below-average, RUE was 29% greater and NPP 15% greater on a non-degraded landscape than on a degraded landscape. These results suggest that both resilient and non-resilient landscapes conform to a similar general model of landscape degradation. That is, averaged over time, primary productivity and rainfall-use efficiency are reduced on degraded resilient landscapes (Holm *et al.* 2003b).

Woody encroachment in southern African rangelands

In many southern African rangelands, woody encroachment remains a serious challenge (Moleele *et al.* 2002; Shackleton and Gambiza 2008; Bennett *et al.* 2012). Several taxa of the genera *Acacia, Dichrostachys, Elytropappus, Euryops, Leucosidea, Passerina, Pteronia* and *Searsia (=Rhus)*, are known to have a deleterious impact on the forage potential of rangeland. Although these woody shrubs do provide other ecosystems services such as woodfuel, biodiversity, carbon sequestration and rain-drop interception, in general their increase reduces the options for graziers (Moleele *et al.* 2002), and goats may replace sheep and cattle as the primary livestock when this woody encroachment occurs (Palmer and Ainslie 2007). However, this process of woody encroachment is not restricted to communal lands, and there is abundant evidence of this type of degradation on freehold land (Lloyd *et al.* 2002; Bennett *et al.* 2012). While land-use plays a role, degradation linked to woody encroachment cannot readily be disassociated from several confounding dynamic climatic factors such as elevated CO_2 concentration, increasing temperature and declining potential evapo-transpiration (Eamus and Palmer 2007; Hoffman *et al.* 2011). Policies which include this carbon sequestration opportunity (Stringer *et al.* 2012) should be more fully explored within regional natural resource policy review.

Landscape patchiness in degraded rangelands

The patchiness of the distribution of resources in landscapes under communal management has been regarded as a sign of degradation (Tanser and Palmer 1999). Increased patchiness is reflected in a high diversity of pixels in the red reflectance band. The detection of these patterns with very high resolution infra-red imagery (Palmer and Fortescue 2004; Kakembo *et al.* 2007) has demonstrated that only small parts of the landscape are now responsible for most of the forage production for livestock. These small patches comprise grazing lawns (Bonnet *et al.* 2010) around homesteads and overnight holding pens, as well as along river beds and around water points. Detection of changes in the distribution and size of grazing lawns can only be achieved with very high resolution (<1m) infra-red imagery, and monitoring of change of these landscape patterns requires repeated analysis of very high resolution near infra-red imagery. The Quickbird satellite does provide the technical options for carrying out this analysis, but the exorbitant cost of the NIR data from this programme has precluded its use in everyday change assessment.

Functional perspectives of rangeland change assessment

One alternative approach to rangeland condition assessment is to identify appropriate indices which use functional concepts to describe landscape performance. Several functional indices have been described, including RUE (Holm *et al.* 2003b; Huxman *et al.* 2004), carbon use efficiency (Tucker *et al.* 2013), the aridity index (Budyko 1974) and water use efficiency (Snyman 1994). Of these, water use efficiency (WUE) is probably the most powerful index for describing the functionality (including ecosystem health, condition and productivity) of drylands and rangelands. WUE defines the ability of an ecosystem to produce above-ground biomass (kg DM) per unit of actual evapotranspiration (mm) (ET_a). It is a unifying concept which has already been calculated for a range of condition classes at single sites in arid and semi-arid rangelands throughout Africa (Snyman 1994) and Australia (Holm *et al.* 2003a and b).

Capture of carbon and evapotranspiration are driven primarily by the leaf area index (LAI) of the canopy (Law *et al.* 2002), and under very high stocking rates of traditional African livestock grazing systems, many rangeland types have both low standing biomass and low LAI. This equates to a landscape that does not optimally use and control the available precipitation to assimilate carbon, and results in high but variable water yield through greater run-off and storm flow events. When the LAI is low, water leaves the landscape and it is not used to drive local evapotranspiration and therefore production. The exception to this is the case of the grazing lawns (Augustine and McNaughton 2004), where short green grass (low LAI) provides dense basal cover and good grazing during the growing season, but does not allow the grazier to accumulate leaf material to attenuate the effect of forage shortage during the dry season.

Only recently have global estimates of ET_a (Mu *et al.* 2011) and net primary production (Running *et al.* 2004) provided the option for preparing landscape scale values of WUE. Bearing in mind the constraints imposed by data deficiency of point measurements of ET_a and NPP, earth observation provides a viable alternative to developing and assessing change in this functional indices. In the past, efforts at developing landscape scale estimates of WUE have been hampered by the scarcity of reliable global net primary production and evapotranspiration response surfaces. With the recent availability of accurate, spatially explicit estimates of ET_a, it is now possible to prepare daily global and regional ET_a surfaces at a spatial resolution of 1 km. We have validated these surfaces for southern Africa using a range of instruments and approaches. In addition, using the principle of light use efficiency, a global annual net primary production (NPP) surface is available for 11 years from 2000-2011. By combining these two products (WUE=NPP/ETa), we have prepared the first spatially explicit estimate of water use efficiency for natural rangelands in southern Africa for 2009. The results indicate that WUE varies spatially, with values ranging from 0.1 kg DM/mm/ha/y in the arid western regions to >8 kg DM/mm/ha/y in the forests and grasslands of the eastern region. Using data from several ground-based measurements of WUE, we validated the national WUE surface at several sites (Palmer et al 2010, Palmer and Yunusa 2011) and show that this is a very useful product for comparing landscape management strategies and condition classes.

This product has the potential to be used to compare the WUE of conflicting land management strategies, and to provide evidence of trends in WUE which are predicted to accompany climate change. While WUE has been used extensively to define efficiency of crop cultivars under irrigation, it has only been applied in a limited way to the assessment of rangeland (Snyman and Opperman 1983, 1984). On the other hand, rain use efficiency has been evaluated for semi-arid rangelands in studies in Australia (Holm *et al.* 2003a; Holm *et al.* 2003b), north Africa (le Houerou 1984) and southern Africa (Palmer and Ainslie 2007). WUE is potentially a more useful functional concept that defines the ecosystem's ability to optimise water use to capture C in a single term. There has been limited opportunity to examine how WUE changes across different land-use and landscape condition classes, and this study explores the impact of land degradation on WUE as a basis for determining the losses in ecosystem services that accompany climate change and rangeland degradation. An understanding of the impact of landscape condition on WUE has been re-explored in southern Africa (Palmer *et al.* 2010; Palmer and Yunusa 2011). The implementation of payment for ecosystem services models (Turpie *et al.* 2008) will necessitate a comprehensive understanding of the WUE of various land condition classes, including those affected by intensive herbivory and cultivation. Following the publication of several new satellite-derived products, it is now possible to prepare landscape-scale estimates of WUE using MODIS NPP and ET products. The results provide the basis for determining the losses in ecosystem services that accompany degradation.

Huxman *et al.* (2004) showed that RUE decreases across biomes as mean annual precipitation increases. During the driest years at each site, Huxman *et al.* (2004) found there was a convergence to a common maximum RUE that is typical of arid ecosystems. That study also determined that in years when water is most limiting, deserts, grasslands and forests all exhibit the same rate of biomass production per unit rainfall, despite differences in physiognomy and site-level RUE. Global climate models (Easterling *et al.* 2000) predict increased between-year variability in precipitation, more frequent extreme drought events, and changes in temperature. Forecasts of future ecosystem behaviour should take into account this convergent feature of terrestrial biomes (Huxman *et al*. 2004). Degraded sites have lower RUE than non-degraded (Holm *et al.* 2003b), and we wish to explore this further using a regional WUE product.

Materials and methods

Degradation in southern African rangelands

The MODIS LAI product provides the opportunity to explore recent trends in green leaf area under different rangeland management regimes. For the purposes of this study, we chose two topographically paired ranches which currently experience contrasting range management regimes. The first, Allanwaters (32.32°S, 26.78°E) has been under communal land tenure for 38 years, and the second, Pink Valley (32.33°S, 26.91°E), has been a commercial ranch under free-hold tenure for >100 years. A comparison of the moderate resolution (1km) MODIS LAI product for 13 years (March 2000- December 2012) at each of the sites was undertaken. In addition, visual pattern analysis of very high resolution infra-red imagery (<1m) was carried out. We also prepared time series profiles for leaf area index (MODIS LAI) at a site with a known history of recent (1950s-present) woody encroachment in the Kei Road area of the Eastern Cape (32.76°S; 27.55°E).

Functional perspectives to rangeland change assessment

A regional WUE surface for southern Africa for 2009 was prepared using the NPP surface of Running *et al*. (2004) and the ET surface of Mu *et al*. (2011) (Fig. 1). In a landscape with distinct, defined zones of different land uses and/or management regimes, Kilpatrick *et al.* (2011) sampled either side of regime boundaries in order to create a large series of paired samples. In this study, we used this approach to compare the MODIS WUE and NPP of two different land management regimes (commercial/ conservation and communal) across regime boundaries in southern Africa. Sites that were selected for comparison included the boundary between Lesotho and South Africa, and the boundaries between several national parks and adjacent commercial rangelands. Significance was tested with a pairwise comparison using t-test with pooled standard deviation. P value uses Holm adjustment method.

Results

Degradation in southern African rangelands

Although the moderate resolution MODIS LAI product failed to show any significant differences in the rangeland condition between the two land tenure regimes (Fig. 2) or in the trend in LAI, field survey of the site did reveal an increase in woody shrubs in the area under communal management (Bennett *et al.* 2012). There was no significant trend in MODIS LAI in these grasslands (Fig. 2) or in an area with a known history of landscape-scale woody encroachment (Fig. 3). Further landscape-scale analysis of another communal site with a longer history of communal regime (>100yrs) revealed a change in the location of productive patches in the landscape. Visual assessment of very high resolution infra-red imagery (Fig. 4a-c) showed

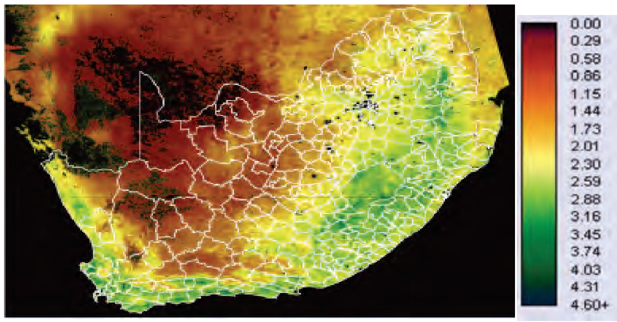

Figure 1. The water use efficiency (WUE)(kg DM/mm ET/ha) of southern African rangelands for 2009. The surface was generated from the MODIS NPP and ET products. WUE incorporates a range of biophysical conditions (vegetation, soil and climate) into a single index which can be used in conjunction with annual actual evapotranspiration to predict the dry matter production (kg) for any site.

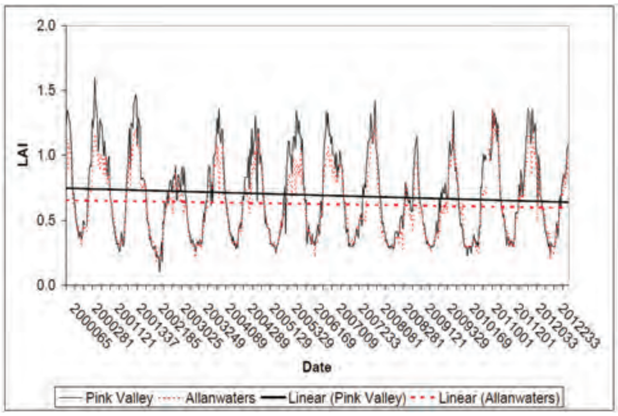

Figure 2. Time series profile (March 2000- December 2012) of the MODIS leaf area index for two farms in the south eastern Cape, South Africa. Farms were matched for topography, rainfall and lithology. Pink Valley has been under commercial management for >100 years, and Allanwaters has been under communal tenure for >35 years. There no trend in LAI on either site.

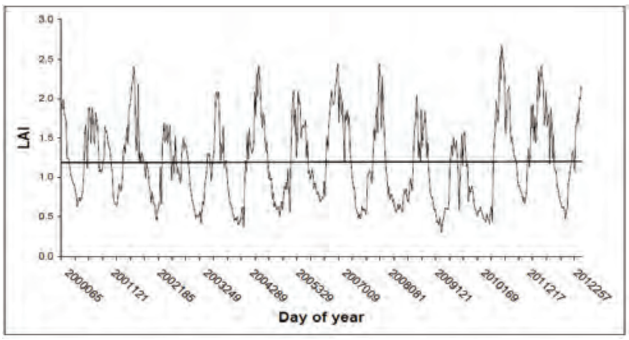

Figure 3. Time series profile (March 2000- December 2012) of the MODIS leaf area index for an area experiencing bush encroachment near Kei Road in the south Eastern Cape, South Africa. There is no trend in LAI over this time period.

that active green patches, comprising mainly short perennial grasses, are concentrated around homesteads and water points, and along water courses. Although this process is also known to occur on the commercial rangeland, it is of limited extent.

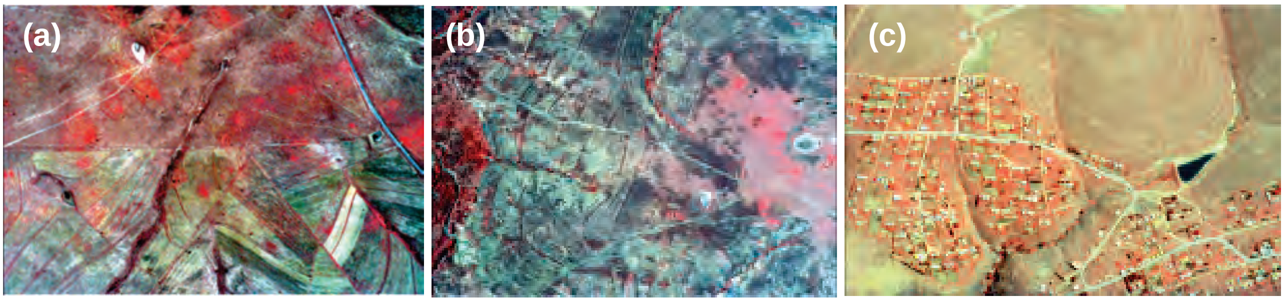

Figure 4a-c. Very high resolution infra-red images of parts of communal rangelands in the Ngnushwa Magisterial District, Eastern Cape, South Africa. Patchiness of the grazing resources is visible as red area around the waters points (a), along contour banks (a and b), adjacent to riparian zone (b) and around the homesteads (c) where livestock concentrate nutrients.

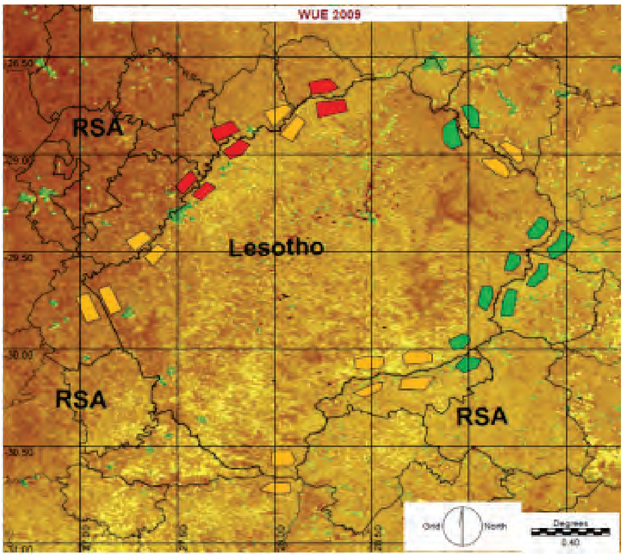

Figure 5. Location of the sampling sites of matched pairs across the boundary between Lesotho (communal) and South Africa (conservation and commercial), plotted on the water use efficiency surface. For red sample blocks $WUE_{Lesotho}$ > WUE_{RSA} ($p<0.001$); orange sample blocks $WUE_{Lesotho}$ = WUE_{RSA}, green sample blocks $WUE_{Lesotho}$ < WUE_{RSA} ($P<0.01$).

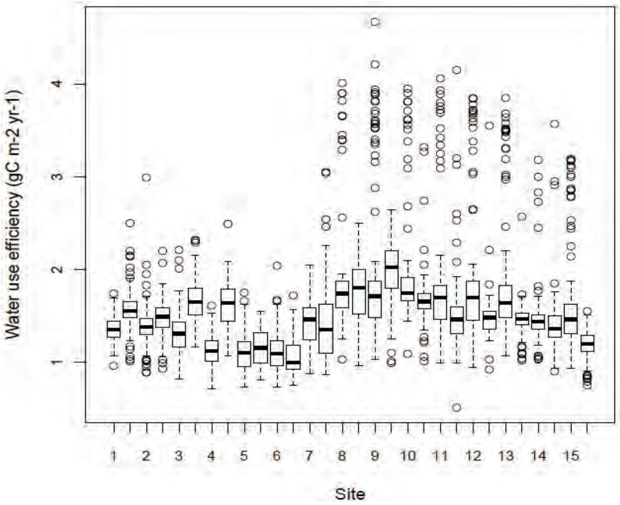

Figure 6. Box and whisker plot of the WUE of 15 sample pairs between South Africa (1st of each pair) and Lesotho (2nd of each pair). Sample pairs 1-6 are located in the semi-arid, low elevation regions, and sample pairs 7-15 are in the high elevation, mesic grasslands.

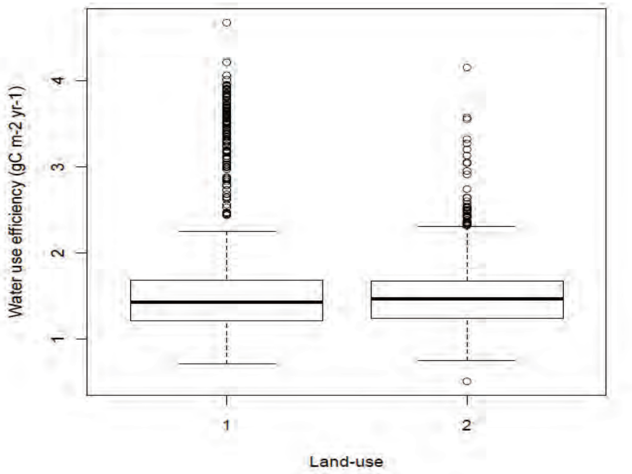

Figure 7. Box and whisker plot of the difference between WUE_{RSA} (1) and WUE $_{Lesotho}$ (2) across the two land-use regimes. Difference significant. $p<0.001$ (t-test with Holm adjustment for p values).

Functional perspectives to rangeland change assessment

The results from the assessment of contrasting rangeland condition classes (old communal versus commercial) on WUE have shown several interesting spatial patterns. WUE is generally lower in those rangelands with a long history of communal tenure (Fig. 5 and 6), with the WUE of five of the matched pairs being significantly lower on communal land in Lesotho than on commercial ranches South Africa. Seven of the 15 matched pairs did not show any significant difference between the two treatments. When all the WUE values are pooled, WUE is significantly lower in Lesotho than in South Africa (Fig. 7).

MODIS NPP is consistently lower on those areas with a long history of communal rangeland management (*e.g.* Lesotho and parts of the former Transkei) (Fig. 8-10). Of the 15 matched pairs that were compared, eight in the commercial sector had a higher NPP than communal area. All other pairs showed no significant difference across the regime boundary. One of these pairs (sample pair 11) was located in the Maluti Drakensberg Transfrontier Park, making this comparison equivalent to a control. When all the NPP values are pooled, NPP is significantly lower in Lesotho than in South Africa (Fig. 10).

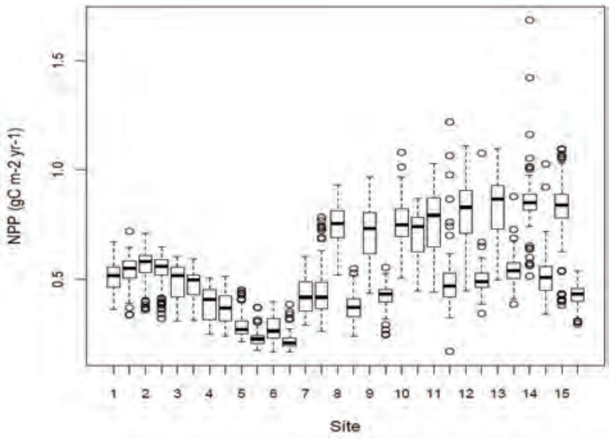

Figure 8. Box and whisker plot of the NPP of 15 sample pairs between South Africa (1st of each pair) and Lesotho (2nd of each pair).. Sample pairs 1-6 are located in the semi-arid, low elevation regions, and sample pairs 7-15 are in the high elevation, mesic grasslands.

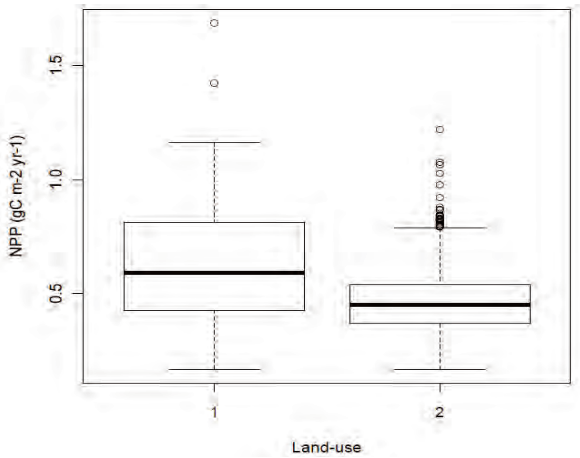

Figure 9. Box and whisker plot of the difference between NPP_{RSA} (1) and $NPP_{Lesotho}$ (2) across the two land-use regimes. Difference significant. P<0.001.

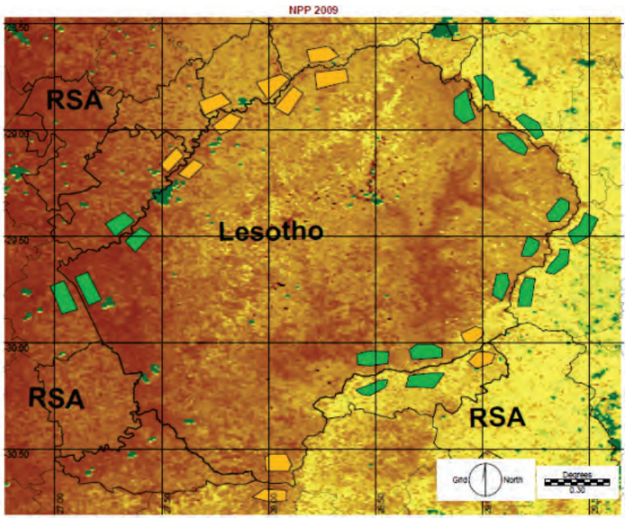

Figure 10. Location of the sampling sites of matched pairs across the boundary between Lesotho (communal) and South Africa (RSA) (commercial and conservation), plotted on the MODIS NPP surface for southern Africa. For orange sample blocks $NPP_{Lesotho} = NPP_{RSA}$, whereas green sample blocks $NPP_{Lesotho} < NPP_{RSA}$ (p<0.001). Note that Site 10 is located in the National Park in Lesotho, and livestock are excluded.

Discussion

Recent trends in resource condition in southern Africa

Analysis of MODIS LAI trends under two different management regimes (recent communal versus commercial) in southern Africa revealed that there is no trend in LAI under either land tenure regime for the length of the MODIS record. Changes in rangeland condition in this area are gradual, and 35 years of a new management regime may not be sufficient to detect resource changes which were evident in ground surveys. In the area experiencing pronounced woody encroachment, there is also no evidence of any trend over the 13 year recording period.

Evidence for the re-distribution of growth patchiness was visible on degraded lands with a long (>100yr) history of communal management. With the increased availability of very high resolution imagery (<1m), the opportunity for assessing and rectifying these patterns using appropriate management actions is encouraging.

While Huxman *et al*. (2004) showed that RUE decreases across biomes as mean annual precipitation increases, in this study WUE increased with the precipitation gradient, with the exception of the winter rainfall region of the west coast of South Africa. This pattern may be linked to the dominance of CAM type plants in the west, but requires further investigation. Although high resolution remote sensing (<20m) has provided the option for accurate pixels by pixel assessment of rangeland condition (Palmer and van Rooyen 1998), moderate resolution imagery (~1 km) with a regular over-pass, provides a better option for developing a functional understanding of changes in rangeland condition.

This study of contrasting rangeland types has shown several interesting spatial patterns. There is a reliable and largely consistent difference in the MODIS NPP between the areas with a long history of communal rangeland management (*e.g.* Lesotho and parts of the former Transkei) and those rangelands with a long history of commercial tenure. The NPP of the communal areas is lower across most of the matched pairs analysed in this study. In addition, the WUE is also generally lower in those rangelands with a long history of communal tenure. The difference between communal and commercial rangeland is not apparent from an analysis of the MODIS LAI product when the land tenure difference has only been applied for circa 35 years.

Using a novel technique which makes the use of different remote sensing techniques, Vanderpost *et al.* (2011) show that rangeland degradation in Botswana was most widespread during the 1980s drought when 25% of the country was affected, decreased to 6.5% in 1994 and increased to 9.8% in 2000. This multi-resolution approach deserves further attention

Conclusion

This study describes a range of remote sensing techniques available for assessing the functionality of rangelands. In southern Africa, three different land-use regimes occur adjacent to one another, and this has provided an opportunity to assess the usefulness of several indices of rangeland function. Water use efficiency is a functional concept with potential for further development as a comparative tool, but requires further testing against across other land-use regime boundaries. Spatial re-arrangement of active green patches has been observed using very high resolution imagery, but the drivers of this process require further elucidation. The data available from the MODIS programme present some interesting possibilities for assessing trends in landscape performance, but the limited time spans result in non-significant trends. All of these approaches can be contained in a toolbox of techniques that may be used in assessing the functionality of rangeland throughout the world.

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