



# Grazing impacts on the susceptibility of rangelands to wind erosion: The effects of stocking rate, stocking strategy and land condition



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## ABSTRACT

An estimated 110 Mt of dust is eroded by wind from the Australian land surface each year, most of which originates from the arid and semi-arid rangelands. Livestock production is thought to increase the susceptibility of the rangelands to wind erosion by reducing vegetation cover and modifying surface soil stability. However, research is yet to quantify the impacts of grazing land management on the erodibility of the Australian rangelands, or determine how these impacts vary among land types and over time. We present a simulation analysis that links a pasture growth and animal production model (GRASP) to the Australian Land Erodibility Model (AUSLEM) to evaluate the impacts of stocking rate, stocking strategy and land condition on the erodibility of four land types in western Queensland, Australia. Our results show that declining land condition, over stocking, and using inflexible stocking strategies have potential to increase land erodibility and amplify accelerated soil erosion. However, land erodibility responses to grazing are complex and influenced by land type sensitivities to different grazing strategies and local climate characteristics. Our simulations show that land types which are more resilient to livestock grazing tend to be least susceptible to accelerated wind erosion. Increases in land erodibility are found to occur most often during climatic transitions when vegetation cover is most sensitive to grazing pressure. However, grazing effects are limited during extreme wet and dry periods when the influence of climate on vegetation cover is strongest. Our research provides the opportunity to estimate the effects of different land management practices across a range of land types, and provides a better understanding of the mechanisms of accelerated erosion resulting from pastoral activities. The approach could help further assessment of land erodibility at a broader scale notably if combined with wind erosion models.

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## 1. Introduction

Wind erosion is widespread across the world's drylands, including the arid and semi-arid rangelands of Australia (Shao et al., 2011). Cultivation and grazing can accelerate wind erosion rates above natural levels by reducing vegetation cover and soil surface stability (Zender et al., 2004; Fister and Ries, 2009; Colazo and Buschiazzi (2010); Webb and Strong, 2011). However, quantifying the impacts of land management on wind erosion rates is an inherently challenging task given the sensitivity of wind erosion to spatial patterns of soils, vegetation and climate variability (Ervin and Lee, 1994; Mahowald et al., 2002; Belnap et al., 2009). Resolving

the impacts of grazing land management on the erodibility of rangelands remains crucial as land use and climate changes increase pressures on dryland environments. This requires improved understanding of the effects of stocking rates and stocking strategies on land erodibility; on how management activities influence wind erosion through their impacts on land condition, and how these impacts vary among different land types in space and time.

Research into the effects of land management on wind erosion has primarily focussed on the impacts of intensive cultivation. These impacts are highly dependent on such management activities as crop cycles and tillage practices (Hagen, 1996; Biielders et al., 2002; Gomes et al., 2003; Zhang et al., 2004). Practical management options have been developed to reduce wind erosion from agricultural fields. These options seek to maintain high surface roughness by establishing critical cover levels (Lyles and Allison,

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1981; Michels et al., 1995; Toure et al., 2011), preserving soil aggregates using reduced tillage systems and chemical fallow (López et al., 2000; Eynard et al., 2004; Feng et al., 2011), and reducing the wind erosivity by establishing ridging or windbreaks (Bielders et al., 2000; Liu et al., 2006).

Knowledge gained from this research has been effective in reducing wind erosion in croplands. Less research has been conducted to quantify the effects of grazing land management on wind erosion (Hoffmann et al., 2008; Vermeire et al., 2005; Belnap et al., 2009). There has been an increasing, and now fairly substantial, body of work on the impacts of grazing disturbance in drylands on biological soil crusts and vegetation, and therefore indirectly on land erodibility (Williams et al., 2008; Tabeni et al., 2014). However, research is yet to focus on the direct impacts of pastoral land management on landscape erodibility.

Rangeland managers can influence the susceptibility of landscapes to wind erosion (herein land erodibility) by changing stocking rates in response to forage supply. Over time, grazing pressure from livestock can affect soil erodibility, the structure and resilience of vegetation communities, land condition, and increase the potential for accelerated soil erosion (Ash et al., 1994). There is a growing body of plot-scale research investigating livestock impacts on soil aggregates and crusts (Eldridge and Leys, 2003; Fister and Ries, 2009; Baddock et al., 2011), while there is a significant body of research into grazing impacts on rangeland vegetation (e.g. Hunt et al., 2014; Orr and O'Reagain, 2011; Rietkerk et al., 2000). These studies have quantified the direct impacts of grazing on rangeland systems and their resistance to degradation pressures. However, few studies have directly addressed grazing impacts on wind erosion at spatial scales that are relevant for land managers (e.g. Li et al., 2003, 2005; Belnap et al., 2009).

To our knowledge, no studies have evaluated the effects of different grazing management strategies on wind erosion. Such information is required to formulate practical erosion management solutions. Difficulties in assessing the long-term impacts of grazing practices on wind erosion, and their variability among land types, has undoubtedly added to the challenge.

Modelling approaches have the potential to provide a means for evaluating the long-term impacts of grazing management strategies on wind erosion across multiple land types. While models have been applied to simulate wind erosion mass flux for rangelands in response to vegetation change, they have not been used to quantify the effects of different grazing management practices on wind erosion (Marticonera and Bergametti, 1995; Shao et al., 1996; Okin, 2008). Webb et al. (2006, 2009) developed the Australian Land Erodibility Model (AUSLEM) to investigate land erodibility changes induced by climate variability and grazing in Australian rangelands. AUSLEM draws input data from a spatially distributed pasture production model (AussieGRASS). The one-dimensional version of this model, the grass and livestock production model GRASP, can be applied to assess pasture degradation risk in response to climate variability and change (Day et al., 1997; Ash et al., 2000; McKeon et al., 2000, 2004; Howden et al., 1999; Webb et al., 2012). We use GRASP here to provide a scenario-based analysis of the effects grazing management practices on landscape elements that control wind erosion across a range of land types.

The objective of this paper is to quantify the long-term impacts of grazing management practices (stocking rate, stocking strategies) and outcomes (land condition) on land erodibility across different land types. We couple the pasture growth and livestock production model GRASP with the land erodibility model AUSLEM to (1) evaluate the long-term effects of stocking rates on land erodibility, (2) identify the sensitivity of land erodibility to different stocking strategies, and (3) determine what effects grazing can have on land erodibility for land in different conditions. We apply the models to make erodibility assessments for four land

types in the rangelands of western Queensland Australia. By evaluating the effects of different grazing strategies on the erodibility of the rangelands at a management relevant-scale, the study provides new information on how grazing activities influence wind erosion and the identification of where and when accelerated soil erosion may occur within these landscapes.

## 2. Study area

The study area covers the semi-arid rangelands of western Queensland, Australia (Fig. 1).

These rangelands are used for cattle and sheep grazing and are a frequent source of dust emissions (McTainsh et al., 1989). Mean annual rainfall varies from 260 mm to 500 mm and the mean maximum temperatures range from 20 °C in winter (June, July, August) to more than 35 °C in summer (December, January, February). The study area can be divided into three bioregions (DEWR, 2007), including the Mulga Lands, Mitchell Grass Downs and the Channel Country. Within these bioregions, four land types are differentiated with a range of soil and vegetation characteristics that influence their sensitivities to climate, land management and wind erosion. The Mitchell Grass Downs land type comprises fertile open grasslands with cracking clay soils, with vegetation dominated by Mitchell grasses (*Astrelba* spp.) and Queensland bluegrass (*Dichanthium sericium*). The Mulga and Gidyea land types both have light sandy clay to medium clay soils, with shrublands and low woodlands (*Acacia* spp.). The Spinifex land type has sandy to sandy loam soils and supports Spinifex (*Triodia* spp.) and desert bluegrass (*Bothriochloa ewartiana*). A summary of the soil and plant species characteristics of the study land types is provided in Table 1.

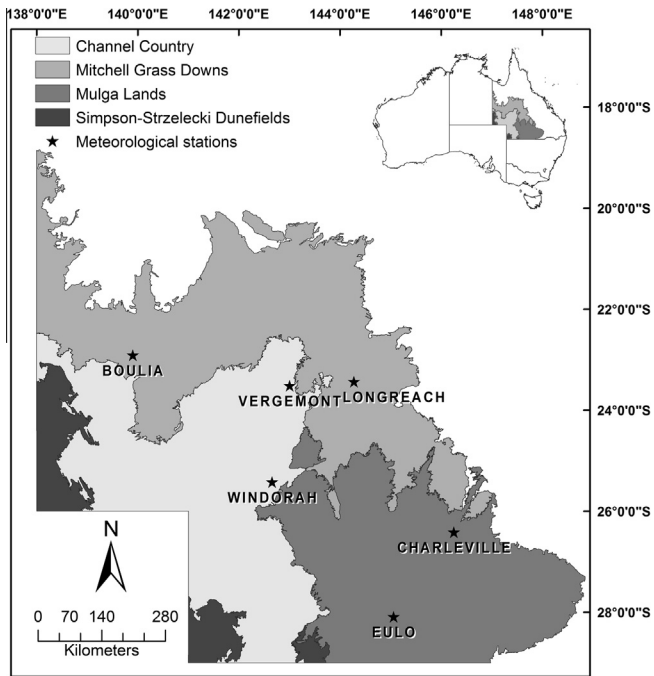
## 3. Methods

### 3.1. GRASP modelling system

GRASP is an empirical point based model which simulates a daily soil–water balance, pasture growth and animal production in response to climate inputs and land management. The model inputs include daily rainfall, minimum and maximum temperature, evaporation, solar radiation and vapour pressure. The GRASP soil water balance simulates, in response to the climate inputs, the processes of runoff, infiltration, soil evaporation and pasture and tree transpiration. The above-ground pasture biomass is modelled as a product of pasture growth, senescence, detachment of standing dry matter, litter decomposition, animal trampling, and consumption. Animal production can be modelled for either sheep or cattle, with cattle being the focus of this study. Forage intake (utilisation) follows feed quality restrictions for the proportion of growth that can be consumed and a limitation for consumption at low pasture biomass levels. The animal liveweight gain is determined as a function of the daily intake, including the duration of grazing. The total biomass consumed is finally calculated as function of the daily intake for the number of livestock specified (by the stocking strategy) equivalent to 200 kg weaner steers.

The GRASP model structure, calibration and validation are described in detail by Day et al. (1997) and Littleboy and McKeon (1997) and summarised by McKeon et al. (2000).

Because GRASP is a one-dimensional pasture growth model it does not explicitly represent the effects of grazing distribution on the pasture, or how this may impact the landscape susceptibility to wind erosion. In real landscapes livestock grazing distributions, for example with respect to the location of watering points, is expected to have a significant impact on spatial and temporal



**Fig. 1.** Study area map shows four bioregions with pastoral land management in the Queensland sector of the Lake Eyre Basin, and the location of the meteorological stations from which climate data was acquired to run the GRASP model simulations (Table 1).

patterns of land erodibility (Landsberg et al., 2003). Here we focus on the immediate impacts of grazing on a sward.

**3.2. GRASP model parameterisation**

GRASP was parameterised for the four study land types: Mitchell Grass Downs, Gidyea, Mulga and Spinifex. The model parameterisations sought to represent the effects of landforms, pasture species and soil attributes (texture, fertility and drainage) on the soil water balance and pasture biomass dynamics that influence land erodibility in each land type. The parameterisations follow those of Day et al. (1997) and Webb et al. (2012). Appendix A summarises the key functional parameters that define the productivity of each land type. Input daily meteorological data related to the land types were sourced from the SILO online database, hosted by the Queensland government ([www.longpaddock.qld.gov.au/silo/](http://www.longpaddock.qld.gov.au/silo/)).

**Table 1**

Study area land types, locations used to acquire meteorological data for the GRASP simulations and their associated mean annual rainfall, coefficient of variation in annual rainfall (%CV) vegetation characteristics and soil types according to the Australian Soil Classification System (Isbell, 2002).

Land type	Meteorological stations	Mean annual rainfall (mm)	% CV annual rainfall	Vegetation type	Main vegetation species	Soil type	Texture type
Mitchell Grass Downs	Longreach	449		Open grassland	<i>Astrebla squarrosa</i> , <i>Astrebla elymoides</i> , <i>Dichanthium sericeum</i>	Vertosol	Clay
	Boulia	266	0.45 0.59				
Gidyea	Vergemont	334	0.54	Shrublands and low woodlands	<i>Acacia cambagei</i> , <i>Sporobolus actinocladius</i>	Tenosol	Light sandy clay to medium clay
Mulga	Charleville	498	0.38	Shrublands and low woodlands	<i>Acacia aneura</i> , <i>Themeda triandra</i>	Kandosol	Light sandy clay to medium clay soils
	Eulo	332	0.49				
Spinifex	Windorah	296	0.53	Grassland	<i>Triodia</i> spp., <i>Bothriochloa ewartiana</i>	Kandosol	Sandy to sandy loam

We used data from six meteorological stations to best represent the rainfall seasonality and inter-annual rainfall variability for each land type (Table 1). Two stations were used to capture the rainfall gradient (wet/dry) within the Mitchell Grass Downs and the Mulga shrub/woodlands. Data were used for the locations of ‘Vergemont’ for the Gidyea shrub/woodland, ‘Charleville’ and ‘Eulo’ for the Mulga shrub/woodland, ‘Longreach’ and ‘Boulia’ for the Mitchell Grass Downs, and ‘Windorah’ for the Spinifex grassland (Fig. 1). For each station a 110-year climate, from 1900 to 2010, was selected over which to run the model simulations. This period was selected to capture the variability of climatic conditions in the study area, where the El Nino-Southern Oscillation (ENSO: 3–7 years cycle) and the Inter-decadal Pacific Oscillation (IPO: 15–30 years cycle) strongly influence rainfall, grass production and episodes of land degradation (McKeon et al., 2004).

**3.3. AUSLEM description**

Land erodibility was modelled using the Australian Land Erodibility Model (AUSLEM). The model was developed and tested by Webb et al. (2006, 2009) to evaluate spatio-temporal patterns of land erodibility in western Queensland. AUSLEM predicts land erodibility for an area by integrating subroutines that account for soil moisture, vegetation, soil texture, shrub and tree cover, and surficial stone cover effects on the susceptibility of the land surface to wind erosion. The model output land erodibility classification is represented on a continuous scale from 0 (not erodible) to 1 (highly erodible). For the current model application we employed AUSLEM to simulate land erodibility as a function of vegetation cover and soil moisture alone (following Webb et al., 2009). These model inputs were sourced directly from GRASP, enabling AUSLEM to be run on a daily time-step.

The grass cover effect on land erodibility ( $E_{gc}$ ) is expressed in AUSLEM as a negative exponential relationship between land erodibility and percentage of grass cover (%gc) (Eq. (1)).

$$E_{gc} = \alpha \exp^{-\beta(\%gc)} \tag{1}$$

where  $\alpha$  and  $\beta$  are regression coefficients (55.873; 0.0938) denoting the equation intercept and rate of change in erodibility given a change in percentage cover (Webb et al., 2009).

The soil water effect ( $E_w$ ) is based on the negative relationship between the water content of source area soils ( $w$ ) and local dust event frequencies in south western Queensland (Webb et al., 2009) (Eq. (2)).

$$E_w = \exp^{-\beta w} \tag{2}$$

where  $\beta$  is a regression coefficient (0.236) denoting the sensitivity of local dust event frequencies to source area soil water content.

Land erodibility ( $E_r$ ) is calculated following the established relationships of Lyles and Allison (1981), Fryrear (1985) and Shao et al. (1996) as in Eq. (3):

$$E_r = E_{gc}(gC) * E_w(W) \quad (3)$$

In the absence of a robust soil erodibility model (Webb and Strong, 2011), we kept the effects of soil texture on land erodibility constant for the simulations, and soil moisture is the only parameter representing soil erodibility in the study. Following Webb et al. (2009), we assume that changes in grass cover and soil moisture at seasonal to inter-annual time scales reflect the variations in soil surface conditions. The simulated land erodibility should capture the main impacts of grazing land management on land erodibility within land types as grazing affects both vegetation cover and soil moisture. However, overall differences between land types may sometimes be greater than predicted by the models due to the different responses of individual soils to trampling disturbance (Gillette et al., 1980; Belnap and Gillette, 1998). Interpretation of AUSLEM output should therefore be confined to the examination of trends in output at a minimum monthly time scale within the same land type.

### 3.4. Model simulations

Three experiments were carried out to simulate the effects of (1) stocking rate, (2) stocking strategy and (3) land condition on the erodibility of the study land types. For each experiment, GRASP was applied to simulate soil moisture and ground cover on a daily time-step over the period 1900–2010. We then aggregated the model outputs to a monthly resolution as input to AUSLEM.

#### 3.4.1. Stocking rate

The first model experiment tested the sensitivity of land erodibility to stocking rate for each land type. The simulations were initiated with land in a non-degraded condition, with the condition responsive to grazing pressure over time. Land erodibility was simulated for a range of stocking rates: from 1 animal adult equivalent (AE; 450 kg non-lactating animal (McLean and Blakeley, 2014)) per 100 hectares (ha) to 30 AE/100 ha. This would capture the variations of stocking rates in the study area which range from 0.2 to 30 AE/100 ha (Bortolussi et al., 2005). The effect of native grazers (principally kangaroos) was represented by a static long-term pasture utilisation estimate of 5% (Munn et al., 2009). This static long-term 'no stock' condition did not take account of climate induced variations in pasture utilisation. The effects of the stocking rates on land erodibility were assessed by calculating the average land erodibility simulated over the period 1900–2010 for each stocking rate and land type, and comparing them to the 'no stock' baseline. This provided an indication of the magnitude and nature of land erodibility responses to increasing stocking rates and the differences between land types.

We also examined the land type responses to increasing stocking rates at a monthly temporal resolution through a case study on the Mulga shrub/woodlands (dry) land type for the period 1942–1945. This short-term analysis enabled an evaluation of the complex interactions between climate, management and land erodibility at a temporal scale most relevant to decision making for grazing land management.

#### 3.4.2. Stocking strategy

The second model experiment examined the land erodibility responses of each land type to two stocking strategies. Again the simulations were initiated with land in a non-degraded condition, and responding to grazing pressure over time. The first represented a strategy in which stocking rates were fixed and unresponsive to

changes in forage availability. The second strategy was flexible, allowing for stocking rates to be adjusted each year in response to the available forage. These strategies, and variations of the two, are commonly applied to manage livestock herds in the study area (McKeon et al., 2004).

The fixed stocking rate maintained the same number of animals through time, regardless of changes in forage availability due to climate variability and/or utilisation by livestock. A low fixed stocking rate and a high fixed stocking rate were used. The low stocking rate was the long-term safe stocking rate for each land type. It represents a stocking level at which the model pastures could be maintained in a good condition, represented by a pasture composition of at least 70% perennial grasses over the 100-year simulation period. The high stocking rate used was selected for each land type in order to maintain a pasture composition of 50% perennial grasses over the long-term. This situation is typical of many grazing enterprises that seek to maximize animal production (Ash et al., 1997).

Under the flexible stocking strategy, stocking rates were adjusted in response to forage availability, targeting a 20% pasture utilisation in each year of the simulations. The level of pasture utilisation was set initially to correspond with the long-term safe stocking rate. Stocking rates were then adjusted yearly according to the forage production over a year's growing season. Within an individual year, the stocking rates were allowed to increase to a maximum of 20% of the initial long-term safe stocking rate or decrease to a minimum of 40% of the initial long-term safe stocking rate. Over the simulation period, the stocking rate was not allowed to fall below 90% of the long-term safe stocking rate, or rise above 50% of the long-term safe stocking rate. Such flexible strategies are increasingly being adopted in the study area (Ash and Stafford-Smith, 1996). Land managers are unlikely to completely destock even during severe drought. However, livestock increases are generally conservative due to large climate variability and technical and economic challenges of varying stock numbers (Campbell et al., 2006).

The effects of the two stocking strategies on land erodibility were evaluated by comparing probability distributions of land erodibility under each stocking strategy for each of the land type/climate type combinations. This provided insights to the sensitivity of the land erodibility responses to different stocking strategies according to the land types.

#### 3.4.3. Land condition

The final experiment was designed to evaluate the direct effect of a change in land condition on the erodibility of rangelands in the study area. Land condition reflects the extent to which historical grazing practices have affected soil stability, pasture species composition and productivity (Ash and McIvor, 1995). These changes influence the land susceptibility to degradation. Declining land condition results from the heavy utilisation of pastures, and is related to the change in perennial plant cover and the influence this has on ground cover, soil moisture and the livestock carrying capacity (McIvor et al., 1995). Changing any of these characteristics will potentially result in accelerated rates of soil erosion.

GRASP was parameterised to represent each of the study land types in four conditions: excellent, good, fair, and poor (following Webb et al., 2012). The land conditions were described in terms of a decline of perennial grasses and a reduction of plant density through the grass basal area. Land represented in the excellent and good conditions had a large percentage of perennial grasses (90% and 75% content respectively) and large grass basal area, enabling large annual pasture growth. They were assumed to be relatively similar to natural rangelands and reflect conservative management practices over time; characterised by low stocking rates and flexible stocking strategies. In contrast, land represented

in the fair and poor conditions had small proportions of perennial grasses (50% and 25% respectively), and a small plant basal areas. These conditions typically result from the overgrazing of pastures through high stocking rates, and a lack of flexibility in stocking strategies especially during periods of drought (Ash et al., 2011).

Land erodibility was simulated over the period 1900–2010 for the four land conditions using the long-term safe stocking rate for each land type. As the land condition was fixed over the simulation period (i.e. no feedbacks between grazing and the land condition), we considered each year in the simulation individually and independently from the previous years. The effect of land condition on rangeland sensitivity to wind erosion was evaluated by comparing the annual average land erodibility over the period 1900–2010 for the four levels of degradation. This provided a means for evaluating the magnitude and nature of land erodibility responses to land condition changes and the sensitivity of the different land types to land degradation.

## 4. Results

### 4.1. The effects of stocking rate on land erodibility

Fig. 2 presents the long-term mean simulated land erodibility (1900–2010) in relation to stocking rate. Increasing stocking rate was found to raise the susceptibility of all of the study land types to wind erosion. The response to increasing stocking rate is non-linear, with the sensitivity of the land types to grazing pressure varying among the land types.

Our results show three general land erodibility level groupings: low (<0.05) for the Mitchell Grass Downs, moderate (0.05–0.15) for the Mulga shrub/woodland (wet) and Gidyea shrub/woodland and high (>0.15) for the Dry Mulga shrub/woodland (dry) and the Spinifex grassland. The land erodibility was consistent with the ranking of land type and climate attributes, from the low erodibility of the relatively fertile Mitchell Grass Downs, to the high end of the erodibility scale with the sandy, and less productive, Spinifex grasslands.

Modelled land erodibility increased in response to increasing stocking rates across all land types. However, the intensity of the response (i.e. the rate of change in erodibility for a given change in stocking rate) varied between land types. The Mitchell Grass Downs display the smallest rate of increase in land erodibility with stocking rate (+0.02 for each additional 1 AE/100 ha) under the wetter modelled climate (Longreach) and +0.04 for each additional 1 AE/100 ha for the drier modelled climate (Boulia). The Mulga shrub/woodland (wet) and Gidyea shrub/woodlands display moderate rates of increase in land erodibility with stocking rate (+0.14 and +0.16 for each additional 1 AE/100 ha respectively). Finally, the Spinifex grasslands display the greatest rate of increase in land erodibility (+0.19 for each additional 1 AE/100 ha).

The non-linear response of land erodibility to stocking rates corresponds with increases and reductions in the rate of change in erodibility. Thus, the rate of change (increase) in erodibility is greater at low stocking rates than at high stocking rates, under which land erodibility appears to plateau. However, the reduced rate of change occurs at different stocking rates according to land type. For the Mitchell Grass Downs (wet and dry), the rate change occurs at 8 and 14 AE/100 ha respectively. The rate of increase in erodibility with stocking rate of the Gidyea land type slows at 8 AE/100 ha. The Spinifex grasslands and Mulga shrub/woodlands plateau out at higher stocking rates ranging from 18 to 22 AE/100 ha.

Examining the land type responses to the stocking rates at a monthly temporal resolution highlights the complex interactions between land type characteristics, climate, management and land erodibility. To illustrate these interactions we evaluate as a case

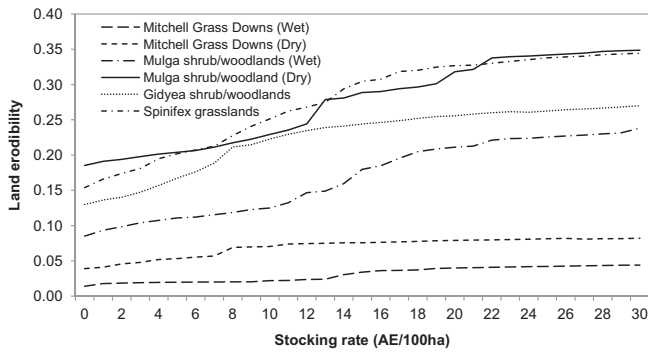
study the modelled land erodibility dynamics of the Dry Mulga shrub/woodlands (dry) land type for the period 1942–1945 (Fig. 3).

Three important observations can be made. Firstly, the large variations in monthly land erodibility (between 0.00 and 0.79) emphasise the smoothing of the long-term averages at the equivalent stocking rates as demonstrated in Fig. 2. Secondly, the monthly land erodibility values track the preceding monthly rainfall. For example, rainfall peaks (December 1942, September 1943) resulted in a reduction in land erodibility over the following months, and this effect is observed across all stocking rates. Conversely, the highest land erodibility values are associated with the driest periods (March 1944–December 1944). Also, increasing stocking rates had a limited impact on land erodibility after extreme wet and dry phases. For example, in the 2 months following the very wet December of 1942 the land was not erodible under any of the stocking rates, and in the months following extended periods of drought (March 1944–December 1944) erodibility was maximal again, with no significant difference in the effect of the different stocking rates. Land erodibility appears to be most responsive to changes in stocking rate during climatic transition phases. During drying transition periods (e.g. April 1943–January 1944) there is a delay in the onset of the highest erodibility at the lower stocking rates (Fig. 3). Thus, land erodibility reaches higher levels sooner under high stocking rate (20 AE/ha) followed by the moderate stocking rate, and no stocking rate. Similarly, during wetting transition periods (e.g. January 1945–August 1945), the modelled land erodibility under the moderate stocking rate, and for land without livestock, decreases more rapidly and the absolute erodibility is lower than under the highest stocking rate. The other land types respond in a similar way. However, the length of the transition periods varies according to the resilience of each land type to stocking rates and climate variability. The Mitchell Grass Downs land type appears to be the most resilient and the Spinifex grassland the least resilient to stocking rate increases due to their soil fertility and plant growth characteristics. This is due to the higher productivity and generally higher cover in this land type.

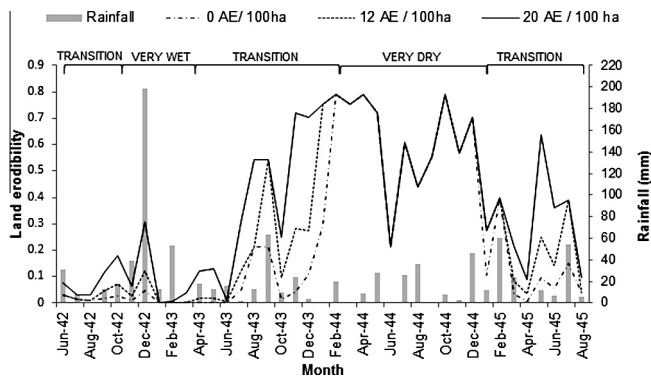
### 4.2. Effects of stocking strategy on land erodibility

Land managers can adopt different strategies to manage forage utilisation by livestock. These strategies essentially relate to the level of flexibility employed in adjusting stocking rates, which is critical in determining grazing pressure and land condition. Stocking strategies can be either fixed or flexible. Under a fixed stocking rate, grazing pressure will vary according to forage availability, with periods of high forage utilisation and reduced ground cover occurring during the transitions between wet and dry periods (Fig. 3). Under flexible stocking strategies, stocking rates are adjusted to maintain a constant grazing pressure. The objective of this strategy is to limit overgrazing during wet-dry transitions and maintain sufficient ground cover to protect the soil surface from erosive winds.

Fig. 4 shows the effect of three modelled stocking strategies on the susceptibility of the study land types to wind erosion. The three strategies sought to maintain a high fixed stocking rate, a low fixed stocking rate and flexible stocking rate targeting 20% forage utilisation in each year of the simulations. The results show that adopting a conservative flexible stocking strategy produced lower land erodibility across all land types; reducing the probability of the highest land erodibility relative to each land type compared to the fixed strategies. Of the two levels of fixed stocking, the high fixed stocking rate (between 20 and 27 AE/100 ha) is more likely to result in increased land erodibility than the low fixed stocking (ranging from 4 to 12 AE/100 ha according to land types).



**Fig. 2.** Long term average land erodibility (1900–2010) modelled with each stocking rate (in Animal Equivalents per 100 ha) for the four study area land types and their climatic variants. *Note:* one Animal Equivalent (AE) is equal to one 450 kg non pregnant animal. Land erodibility values can from 0 (not erodible) to 1 (highly erodible).



**Fig. 3.** Monthly rainfall and land erodibility for three stocking rates (0 AE/100 ha, 12 AE/100 ha, 22 AE/100 ha) for the Wet Mulga land type between June 1942 and August 1945.

The use of a high fixed stocking rate with a pasture utilization twice that of the low fixed stocking rate is shown to have a greater effect on erodibility than the difference between the low fixed stocking rate and the flexible but conservative strategy under all land types. However, the responses of land erodibility to the stocking strategies were found to vary among land types. Employing the flexible stocking strategy in the Mitchell Grass Downs (wet) and Spinifex grasslands produced a similar proportion of high, moderate and low erodibility land to the fixed low stocking rate. However, these land types were very sensitive to the high fixed stocking rate. The Spinifex grassland for example displayed a major increase in land erodibility, increasing the probability of the land being erodible by 400%.

The other land types (Mulga shrub/woodland and Gidyea shrub/woodlands) were very responsive to the use of a conservative flexible strategy. Using a flexible stocking strategy reduced the proportion of time in which land had a high and moderate erodibility compared to the fixed strategies, with the high fixed stocking rate having the highest probability of high erodibility values. Importantly, the benefits of adopting a flexible stocking strategy for reducing land erodibility are still dependent on stocking rate and pasture utilisation. Targeting a high pasture utilisation with a flexible stocking strategy may have similar or less benefit than fixed stocking strategies; i.e. result in increased susceptibility to wind erosion. The success of the strategy depends strongly on the level of flexibility that can be employed in adjusting stocking rates in response to climate variability and vegetation growth (e.g. Fig. 3).

### 4.3. Land condition and erodibility

Land condition describes the state of land in terms of pasture species composition, productivity and cover, and often determines the susceptibility of land to wind erosion. Land condition can change in response to historical and current management, with the degree of change (e.g. pasture degradation) being determined by the resilience of land types to management pressures. Land in excellent or good condition typically reflects the use of conservative stocking rates and flexible stocking strategies, whereas land in fair or poor condition may indicate the use of high stocking rates and non-flexible strategies.

Our modelling results show that land erodibility may increase with declining land condition across all of the study land types (Fig. 5). Land in fair and poor condition was found to be consistently more erodible (between 0.03 and 0.27) than land maintained in excellent or good condition (variation between 0.02 and 0.13). Declining land condition was found to have the greatest effect on land erodibility, which increased by 27–69% across all land types between the good and fair conditions. The land erodibility increased between by 7–34% between all other land conditions. However, the magnitude of increase in erodibility in response to a decline in land condition varied between land types, i.e. land types with similar erodibility under excellent land condition can have widely different erodibility under poor land condition. The Mitchell Grass Downs (dry) and the Spinifex grassland were the most sensitive to changes in land condition, showing increases in land erodibility of up to 139% and 176% respectively with a change from land being in excellent to poor condition. The absolute erodibility values for the Mitchell Grass Downs were, however, low. The remaining land types (Gidyea shrub/woodland, Mulga shrub/woodland) showed an overall increase of land erodibility, between 90% and 92%, for the same decline in land condition.

## 5. Discussion

Coupling a grass production model with a land erodibility model enabled us to estimate the effects of different grazing land management strategies on land erodibility across western Queensland. Our results have shed new light on the mechanisms driving accelerated erosion in the Australian rangelands and provide a basis for future landscape-scale analyses of pastoral management impacts on wind erosion. Specifically, our simulation analysis has provided quantitative measurements of land management impacts on land erodibility, and a basis for better understanding accelerated wind erosion in grazed dryland environments. Our results have shown that maintaining land in a good condition and adopting low and/or flexible stocking rates can help reduce land erodibility and limit accelerated erosion. They also demonstrate the relative sensitivity of different land types to grazing pressure and when they may become susceptible to wind erosion. The focus of this study has been the arid and semi-arid region of western Queensland. In higher rainfall areas, wind erosion is not an important factor and so grazing management may not have much, if any, effect on wind erosion.

Maintaining land in a good condition and improving land condition were shown to reduce the susceptibility of rangelands to wind erosion over all land types. However, failing to adapt management to declining land condition was found to increase land erodibility and may expose the land types to accelerated wind erosion. Land in a good condition may be considered close to the natural baseline in terms of vegetation species composition, cover, soil moisture and other characteristics controlling wind erosion. Good condition land has a greater resilience than degraded land to climatic variability and grazing pressure (Vanderpost et al., 2011), and

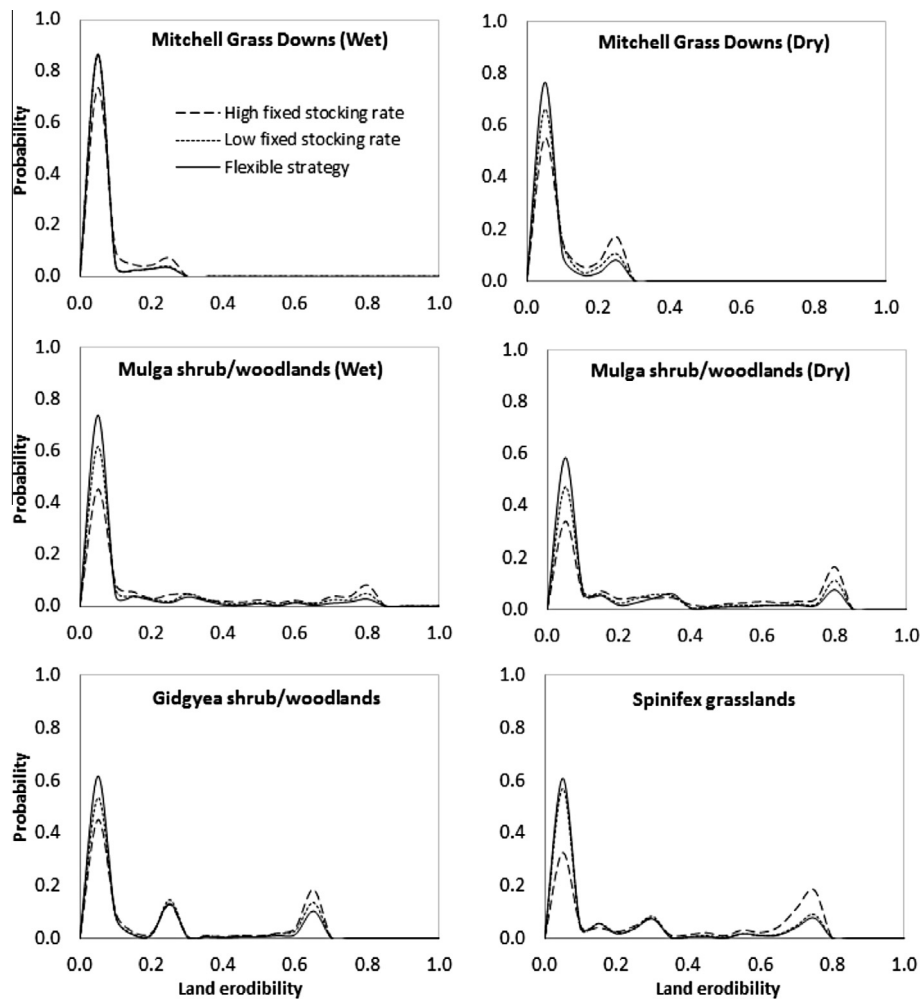


Fig. 4. Probability distributions of simulated land erodibility for three stocking strategies between 1960 and 2010 for the study land types and climate variants.

therefore tends to be least susceptible to wind erosion. As land condition declines, our results show that land erodibility increases and may amplify rates of wind erosion. However, the land erodibility response to declining land condition is nonlinear and displays threshold-type behaviour across all land types. This trend, also described by Li et al. (2005), and indicates that the rate of change in land erodibility is related to ecological and geomorphic changes within landscapes which affect their erodibility (Sasaki et al., 2008; Peters et al., 2004, 2007). In particular, a change in plant composition from perennial to annual dominated systems and shrub encroachment can significantly increase land erodibility (Okun et al., 2006; Ravi et al., 2011; Webb et al., 2014).

Annual plants are sensitive to drought conditions and their presence can result in low vegetation cover levels and greater soil exposure, both seasonally and during extended drought (Ash et al., 1994; Scanlon et al., 2005). This typically increases the land erodibility. Our results support field studies in showing that an increase in annual plants (reduction in perennial grasses) can increase land erodibility in the long-term. For example, Belnap et al. (2009) recorded larger wind erosion rates from degraded sites containing a high frequency of annual plants over a 10-year period. In practical terms, such a change in rangeland plant community composition could translate to a reduced livestock carrying capacity (Campbell et al., 2006; McKeon et al., 2009) and would require a change in stocking strategy in order to reduce land erodibility and increase landscape resilience. Consequently, maintaining or improving land condition can limit the impacts of grazing on land

erodibility and build resistance to accelerated erosion (Bestelmeyer, 2006; McIvor et al., 1995). Failing to adapt management to declining land condition could lead to an increase of land erodibility and an amplification of accelerated erosion (Li et al., 2003, 2005).

Maintaining low stocking rates can reduce the susceptibility of rangelands to wind erosion and minimise accelerated soil erosion. Fig. 3 suggests that using low stocking rates can also improve landscape resilience to disturbance and drought. This finding is supported by Hoffmann et al. (2008) who demonstrated that low stocking rates can be used to maintain surface roughness and minimise wind erosion, while high stocking rates may lead to the formation of wind erosion hot spots (Gillette, 1999). The nonlinear response of erodibility to stocking rate can be attributed to changes in land condition that may occur following periods of extended overgrazing under high stocking rates. The plateau in the erodibility response to high stocking rates is indicative of a decline in land condition (Fig. 2). That is, land erodibility cannot increase further as grazing pressure reaches a maximum and grass cover reaches a minimum. The erodibility values at which the plateaus occur appears to be low in Fig. 2 because the values represent long-term averages. We expect that land erodibility would be higher over shorter periods of time (e.g. Fig. 3).

The response of land erodibility to stocking rate was also found to vary through time. These effects are summarised in a conceptual model presented in Fig. 6. The effects of grazing on land erodibility are limited during extreme climatic episodes (very wet/very dry).

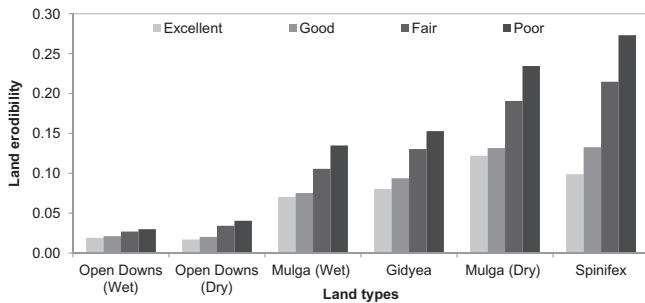


Fig. 5. Long term average land erodibility (1900–2010) in relation to land condition for the study land types and climate variants.

The land erodibility controls are at similar levels to the natural baseline as the climate drivers outweigh the management effects on wind erosion. Extremely wet conditions promote increased ground cover which reduces land erodibility (as suggested by our simulations). Extremely dry conditions naturally reduce vegetation cover and soil moisture and drive land erodibility to its maximum level. The impacts of management are difficult to discriminate from field studies under such severe drought conditions.

Land erodibility appears to be most sensitive to grazing during climatic transition periods (Fig. 6). As climate moves from wet to dry phases through time ( $x$ -axis), the land erodibility increases until natural wind erosion may occur. A hypothetical wind erosion threshold would occur at some point along the land erodibility scale which would vary between land types according to their inherent erodibility parameters. During this drying phase, adopting high stocking rates can increase land erodibility, potentially creating an episode of accelerated erosion.

As the climate moves from dry to wet phases through time, land erodibility may also decrease more slowly as ground cover takes longer to recover from very low levels. Our results suggest that livestock grazing can slow reductions in land erodibility (increase in ground cover) due to the ongoing utilisation of forage. This grazing effect could be further amplified by changes in soil erodibility. However, the duration of potential accelerated erosion periods would depend on the stocking rate used. This finding indicates that land managers can limit the impact of grazing intensity on land erodibility and reduce accelerated erosion risk by employing stocking strategies that are responsive to forage availability and stocking rates which do not significantly reduce vegetation cover levels during periods of drought. This is consistent with rangeland

ecology literature on best practice management for controlling soil erosion (Morton and Barton, 2002).

Coupling GRASP with AUSLEM enabled us to determine the potential responses of land erodibility to grazing management. The approach also provides a basis for a better understanding of future changes in landscape erodibility in response to the interacting effects of climate variability, climate change and grazing land management. Webb et al. (2012) simulated forage production under various climate change scenarios for several land types in Queensland including the four in this study. They show that under hotter (+3 °C) and wetter (+17% mean annual rainfall) climate, forage production could increase up to 60%, which should reduce the sensitivity of landscape to wind erosion and reduce accelerated wind erosion rates across if current grazing practices are maintained. Under a warmer (+2 °C) and drier (−7% mean annual rainfall) climate or a hotter (+3 °C) and drier (−46% mean annual rainfall) climate, Webb et al. (2012) reported potential decreases in forage production as large as 90%. Combined with expected reductions in soil moisture under this scenario, we might expect land erodibility to increase across the study area. There is, however, large variability in these potential forage production responses to climate change, including projected climate change itself. This large variability is due to the functional characteristics (soil and plant growth attributes) that moderate the land type responses to climate and land management, and could be expected to result in a range of erodibility responses across the rangelands. Adaptation of management practices (i.e. reduction of stocking rates, and adoption of flexible stocking strategies) would be required to reduce the impacts of grazing and potential environmental degradation. Our results show that maintaining land in a good condition will be the best strategy for land managers to reduce the risk of future wind erosion.

Adopting a flexible stocking strategy can be effective in reducing the susceptibility of the study land types to wind erosion. This is well illustrated by the severe episode of wind erosion in the Australian Mulga country during the droughts of the 1940s, in which inflexible stocking strategies were reported to be the main cause of widespread wind erosion and land degradation (Beadle, 1948; McKeon et al., 2004). Our results show that different land types display a diversity of land erodibility responses to different stocking strategies, reflecting their different sensitivities to razing pressure and disturbance. Our results suggest that for most land types, some level of flexibility in stocking rates in response to climate variability will likely reduce land erodibility and the risk of accelerated erosion. However, some land types, e.g. the Mitchell

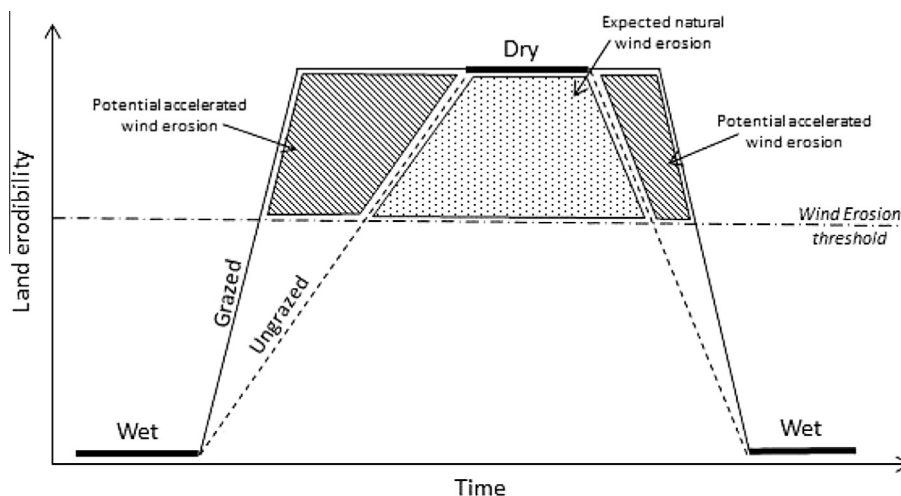


Fig. 6. Conceptual diagram illustrating the land erodibility response to grazing pressure during a climatic transition typical of seasonal precipitation regimes in many areas of the world's rangelands.



Grass Downs (wet) and the Spinifex grasslands, may at times be more responsive to stocking rate than changes in the flexibility in which they are implemented. This variability of response among land types, as well as climate, was also observable in other simulations (Fig. 2, Fig. 5). The importance of this variability has been demonstrated elsewhere for wind erosion assessments in the United States, supporting the case that land type and soil degradation influences on vegetation responses to grazing underpin management impacts on wind erosion (Ash et al., 1994; Webb et al., 2014).

The modelled land erodibility responses to different land management follows expected patterns for the land types given their plant growth characteristics and local climate variations. The use of long-term trends allowed us to successfully capture the nature of landscape responses to climate variability and grazing through changes in vegetation cover and soil moisture. However, the absence of dynamic soil erodibility inputs in response to management practices is a significant limitation of the study as the results do not integrate the variation of different soil responses to disturbance. Fine textured soils (e.g. Mitchell Grass Down) typically respond more to disturbance through changes in threshold ( $u_{*t}$ ) and the availability of loose erodible material compared to coarse textured soils (e.g. Spinifex grassland) (Belnap and Gillette, 1998). Therefore, accelerated erosion should be greater than suggested by our results on land types with finer soil textures (i.e. Mitchell Grass Down > Mulga and Gidyea shrubland/woodland > Spinifex grassland). Soils with either physical or biological crusts should show a larger response to trampling disturbance than non-crusts soil for any of the studied soil types (Leys and Eldridge, 1998). As crusting and trampling disturbance vary in space and time, we assume that the temporal variation in the soil surface erodibility is captured in part through seasonal variations in precipitation that have influenced the pasture growth and soil moisture.

This paper has demonstrated the application of a dynamic vegetation growth model for quantifying land use impacts on wind erosion. The method could be extended to other land types in Australia, and eventually be integrated in a geographical information system to include the spatial and temporal variations of grazing. The methodology could also be used to evaluate the impacts of land use and land cover change. For example, by combining AUSLEM with Agricultural Production Systems sIMulator (APSIM) assessments of management practices in croplands, improved pastures and rangelands (Keating et al., 2003). Similar methods could also be used to investigate the impacts of land use on wind erosion in other regions using as the capabilities of Environmental Policy Integrated Climate (EPIC) model in the United States (Wang et al., 2006a,b), Crop Growth Monitoring System (CGMS) in Europe or the Soil Water Balance (SWB) Model in South Africa (Campbell and Diaz, 1988).

## 6. Conclusions

This paper has provided new insights into the impacts of grazing land management on potential wind erosion. Our results indicate that using high stocking rates and inflexible stocking strategies may result in land degradation and increase the susceptibility of rangelands to wind erosion. Despite these common trends, we found land erodibility responses to grazing management to be complex and influenced strongly by land type and climate characteristics. A diversity of land erodibility responses was observed among the study land types, indicating different tolerances to grazing management and wind erosion. Overall, land that is maintained in a good condition, dominated by perennial grasses,

may be most tolerant to grazing pressure and least susceptible to accelerated wind erosion.

Our results also provide a greater understanding of the interactions between climate, management and land type characteristics as they affect land susceptibility to wind erosion. Our simulations show that the sensitivity of land to accelerated wind erosion particularly increases during climatic transition periods when the land erodibility controls are most sensitive to external stressors. Grazing effects appear to be limited during extreme climatic periods as the land erodibility is mainly driven by the climatic influence on vegetation. The study demonstrates the importance of understanding the impacts of pastoral land management on the erodibility of arid and semi-arid rangelands before being able to quantify accelerated wind erosion. It also underlines the importance of accounting for the impacts of land management relative to land types and climate when assessing accelerated wind erosion. Importantly, our results provide insights into the effects of stocking rates, stocking strategies and land condition at a scale most relevant to land managers, and in the context of management-relevant strategies that can be used to inform wind erosion assessments and mitigation efforts.

## Appendix A

Land type functional characteristics used to parameterise the GRASP model to represent the four study land types across the western Queensland rangelands.

Land type functional parameters for GRASP	Mitchell Grass Downs	Gidyea	Mulga	Spinifex
<i>Maximum Plant Available Water (MPAW)</i>				
Total MPAW (mm)	260	68	170	196
Layer 1 MPAW (mm)	34	13	17	12
Layer 2 MPAW (mm)	133	35	68	34
Layer 3 MPAW (mm)	93	20	85	150
<i>Maximum Pasture Yield (kg ha<sup>-1</sup>)</i>				
(Max N uptake/%N at zero growth) × 100	2750	1500	1833	2571
<i>Soil fertility</i>				
Potential (maximum) N uptake (kg ha <sup>-1</sup> )	22	15	22	9
Potential daily regrowth rate per basal area (kg ha <sup>-1</sup> day <sup>-1</sup> )	5	2	2	3
<i>Pasture species</i>				
%N at zero growth (minimum N)	0.8	1	1.2	0.35
%N at maximum growth (maximum N)	0.9	1.1	1.3	0.45
Transpiration efficiency (kg ha <sup>-1</sup> mm <sup>-1</sup> of transpiration at VPD = 20 mb)	21	12	8	6
<i>Trees</i>				
Tree Basal Area (m <sup>2</sup> ha <sup>-1</sup> )	0	2	4	2

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