CSIRO PUBLISHING

The Rangeland Journal, 2021, **43**, 185–209
https://doi.org/10.1071/RJ21036

Prospects for sustainable use of the pastoral areas of Australia's southern rangelands: a synthesis

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Abstract. There is growing recognition of the need to achieve land use across the southern Australian rangelands that accommodates changing societal preferences and ensures the capacity of future generations to satisfy their own preferences. This paper considers the prospects for sustainable use of the pastoral lands based either on continued grazing or emerging, alternative land uses. After an overview of the southern rangelands environment, the status of the pastoral industry, its environmental impacts, and key issues for pastoral management, we propose four principles and 19 associated guidelines for sustainable pastoralism. Although some continued withdrawal of land from pastoralism is anticipated, we expect that pastoralism will continue throughout much of the region currently grazed, particularly in the higher rainfall environments in the east. Within these areas, sustainable pastoral land use should be achievable by the application of four broad management principles, as follows: (1) manage grazing within a risk management framework based on the concept of tactical grazing, (2) develop infrastructure to allow best management of both domestic and non-domestic grazing pressure, (3) incorporate management of invasive native scrub, where required, into overall, ongoing property management and (4) manage grazing to enhance biodiversity conservation at landscape scale. Application of these principles and guidelines will require the development of appropriate policy settings, particularly in relation to kangaroo management, climate change, and natural resource governance, together with innovative approaches to research, development and extension. Policy development will also be required if the new industry of carbon sequestration is to deliver socio-ecological benefits without perverse outcomes. Other emerging industries based on renewable energy or ecosystem services appear to have considerable potential, with little risk of adverse ecological consequences.

Keywords: grazing management, total grazing pressure, emerging land uses, infrastructure, invasive native scrub, biodiversity conservation, policy.

Received 30 June 2021, accepted 2 December 2021, published online 22 December 2021

Introduction

The southern rangelands of Australia, defined by Hacker *et al.* (2019*a*) as those semiarid and arid areas that lie inland of the wheat–sheep zone and south of the summer-dominant rainfall zone (Fig. 1), occupy 4.3 million square kilometres or ~57% of mainland Australia[1]. Long-established industries in this region have included extensive grazing, practised over 54% of the area (ABARES 2016; Fig. 1), mining and tourism, with estimated annual values of A\$1.4 billion, A\$66.0 billion and A\$1.9 billion respectively[2]. The region includes several important towns, but, overall, is very sparsely populated, accounting for less than the 1.7% of the Australian population (approx. 26 million), and 16.9% of the total population of Indigenous Australians, that has been estimated to reside in the whole of the Australian rangelands (derived from Foran *et al.* 2019, table 2).

Other land uses include conservation estate (national parks and a range of other areas protected or managed for conservation, 29%), traditional Indigenous uses (14%) and a range of minor

[1]The southern rangelands so defined are more extensive than other definitions in the literature, e.g. 'an approximate geography bounded to the north by the Northern Territory–South Australia border as extended west through Western Australia, and east through Queensland' (Foran *et al.* 2019) or '[rangeland] areas south of the Tropic of Capricorn' (Waters *et al.* 2019).

[2]Derived from Foran *et al.* (2019), appendix 1. Value for extensive grazing is for 2016–17 and assumes that all rangeland sheep meat and wool production, and 20% of cattle production, occurs in the southern rangelands which, as defined here, represent 68.9% of the Australian rangelands as defined by Foran *et al.* 2019 (their table 3). Mining includes oil and gas; the figure is for 'value added' and production in the southern rangelands is assumed proportional to area; data are for 2014–15. The value of tourism is 'gross value added'; value for the southern rangelands is assumed proportional to area; data are for 2016–17.

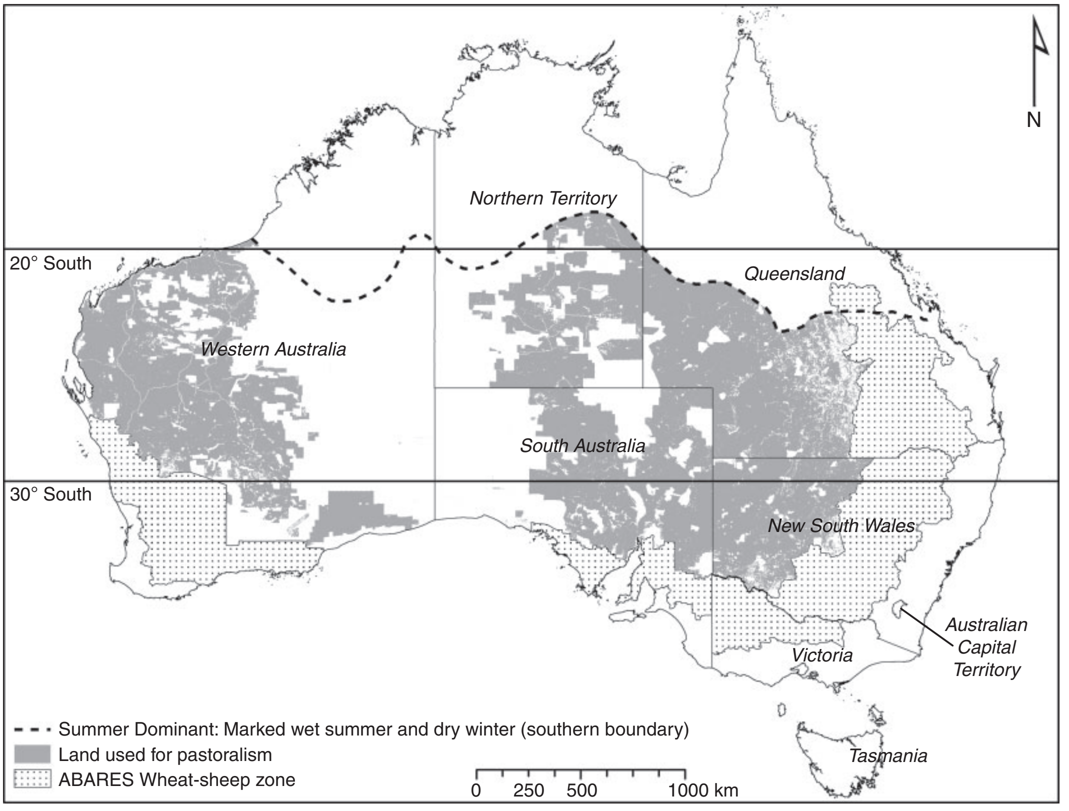

Fig. 1. Approximate boundaries of the southern rangelands. The northern boundary approximates the southern edge of the summer-dominant rainfall zone as defined by the Bureau of Meteorology. Elsewhere the inland boundary of the wheat-sheep (or mixed farming) zone as defined by the Australian Bureau of Agricultural and Resource Economics Sciences (ABARES) provides a reasonable approximation. (Source: Hacker *et al.* 2019*a*).

uses including defence land, cropping and horticulture, plantation forestry, mining, and services/infrastructure/utilities (ABARES 2016). Land held by Indigenous people under national, state and territory land rights legislation, and determined Native Title (exclusive possession), will be more extensive than the figure for 'traditional Indigenous uses' given above because Foran *et al.* (2019) estimated the extent of the former at 33.6% for the rangelands as a whole. There is probably some overlap, in this case, with those areas classified here (Fig. 1) as used for grazing, or included in the conservation estate. Over 8 million hectares of land are currently managed by private conservation organisations (Australian Wildlife Conservancy 2021; Bush Heritage Australia 2021), representing a small but growing land use that probably also overlaps land used for grazing as defined here because much was originally, or still is, held under pastoral lease.

Discussion of sustainable land use in this region has generally occurred in the context of pastoral production. However, in recent decades, societal preference for non-provisioning ecological services has focussed attention on issues such as conservation of biodiversity, Indigenous and non-Indigenous cultural heritage, landscape aesthetics, and space in a crowded world (Holmes 2002), which apply equally to non-grazed areas. This broader discussion is reflected in the systemic challenges within Australian rangelands identified by Foran *et al.* (2019), including (1) undermining of the social licence to operate by those not managing resources appropriately, (2) providing opportunities for a growing and more youthful Indigenous population, (3) managing opportunities and threats associated with improved technologies, (4) governance resulting in human and financial capital leakage, and (5) improving human capacity and capability. In a similar vein, Nielsen *et al.* (2020) considered the key challenges facing Australia's rangelands to be related to (1) supporting local communities, (2) managing natural capital, (3) climate variability and change, (4) traditional knowledge, (5) governance, and (6) research and development. These challenges will define the environment in which sustainable land use will need to be achieved.

Low profit margins for rangeland livestock production, identified by Briske *et al.* (2020) as one of several challenges for rangelands used for livestock production throughout the developed world, have seen extensive parts of the grazed southern rangelands (e.g. the Western Division of New South Wales, south-western Queensland and the Gascoyne–Murchison region of Western Australia) subject to government interventions in recent decades aimed at improving economic, social and environmental outcomes. Some of these interventions achieved a measure of success (e.g. URS 2004, 2015) but, generally, they failed to resolve the structural issues affecting the pastoral industry at regional scales.

Recent decades, however, have also seen an evolutionary transformation of the pastoral industry with a contraction of wool production and expansion of beef, goat and sheep meat production, the latter being associated with the widespread adoption of new breeds that pose specific issues for sustainable

Table 1. Definitions of terms used in the paper

Term	Definition
Carrying capacity	The average number of animals (expressed in terms of some equivalence scheme, e.g. dry sheep equivalents) that can be carried in the long-term without degrading the resource (or which is compatible with the management objectives) (SRM Glossary 2020). The same concept can be applied to shorter periods, say one year.
Degradation	Depletion of perennial vegetation and soil erosion under conditions of drought and high grazing pressure.
Dingo/wild dog	Although these terms are often used interchangeably, wild canids in Australia are overwhelmingly of the distinct dingo lineage; both feral domestic dogs and first-generation dingo × dog hybrids are rare (Cairns *et al.* 2021).
Invasive native scrub (INS)	Native shrub and tree species that encroach or increase in density in previously open areas, or that invade plant communities in which the species do not normally occur (WLLS 2019).
Landscape function	The capacity of landscapes to capture, retain and use resources such as water and nutrients (Tongway and Ludwig 1997).
Stocking density	The number of animals grazing a specified land area at a point in time (SRM Glossary 2020). Stocking density is more usefully applied to individual management units.
Stocking rate	The number of animals grazing a management area, over a specified time period; expressed in terms of animal units per unit area per time period (SRM Glossary 2020). Stocking rate can be related either to the entire property or individual management units.
Total grazing pressure	'The combined grazing pressure exerted by all managed and unmanaged herbivores on vegetation, soil and water resources' (Fisher *et al.* 2004), relative to forage supply (Hacker *et al.* 2019*a*).
Unmanaged goats	Unmanaged goats exist in free-roaming wild populations, are not born as a result of a managed breeding program, and are not subjected to any animal husbandry procedure or treatment.
Rangeland goats	The Australian rangeland goat is a composite incorporating dairy, fibre and meat goat breeds, which has become naturalised throughout Australia's rangelands. In extensive production systems does originating from free-ranging herds can be joined with selected bucks 'behind wire' as part of commercial enterprises. The term may also refer to unmanaged goats that are mustered and sold.

land use (Alemseged and Hacker 2014; Hacker and Alemseged 2014). These changes have been largely driven by the social and economic condition of the industry, reflected in issues such as reduced relative profitability of wool production and ability to control predation of sheep flocks by dingoes and wild dogs (see definitions in Table 1) (Forsyth *et al.* 2014), limited labour availability on pastoral properties, and, in places, the declining state of pastoral infrastructure. Sheep production has largely contracted to areas protected by the 5600 km 'dog-proof fence' in South Australia, New South Wales and Queensland (Hacker 2010). In some places, novel industries have emerged alongside pastoralism (e.g. carbon sequestration in native forests), and more novelty has been foreshadowed (e.g. renewable energy production; Garnaut 2019), which may complement ongoing changes within the pastoral industry itself.

In this paper, we consider the prospects for achieving sustainable land use across the southern rangelands of Australia, particularly within the pastoral areas, but recognising that some emerging land uses could be adopted more broadly. We are concerned to promote land use and management that accommodate changing societal preferences today, while maintaining or enhancing the capacity of future generations to satisfy their preferences. We provide an overview of the environment of the southern rangelands, the pastoral industry, emerging land uses, and the historical impacts of pastoralism. We then propose principles and guidelines to address the key issues for pastoral land use, and consider the prospects for sustainability more generally based either on pastoralism or alternative land uses.

Characteristics of the southern rangelands and the pastoral industry

Vegetation and soils

Vegetation and soil characteristics of the southern rangelands are summarised in Table 2 (a and b, respectively). Compared with areas that remain ungrazed, areas used for pastoralism contain more extensive areas of soils with red duplex, gradational (both calcareous and non-calcareous), and uniform (both fine, cracking and medium textured) profiles, and much smaller areas of soils with uniform, coarse textured profiles. The corresponding differences in vegetation result in greater areas of *Acacia* (predominantly mulga, *Acacia aneura*) woodlands and shrublands, chenopod shrublands (characterised by the genera *Atriplex* and *Maireana*), tussock grasslands (with *Astrebla* spp. in the north-east and a range of C_3 species elsewhere), and *Eucalyptus* forests and woodlands (particularly in the eastern semiarid zone) within the pastoral rangelands, and smaller areas of hummock grasslands (predominantly *Triodia* spp) and mallee communities (dominated by particular growth forms of *Eucalyptus*). This differentiation between pastoral and non-pastoral areas reflects the relative grazing potential of the broad vegetation types identified.

Climate

Average annual rainfall (AAR) varies from <200 mm to ~500 mm across the southern rangelands, with the higher-rainfall environments occurring on the eastern margin (Fig. 1). Inter-annual variability typically varies inversely with the average, but is not higher than in several other desert regions (van Etten 2009). Nevertheless, low and variable rainfall is a fundamental determinant of land use throughout the southern rangelands. Additionally, rainfall throughout the region is not distinctly seasonal, which creates difficulties for pastoral management. Even though winter rainfall is generally more effective for plant growth, forage can be produced at any time of year and stocking decisions can, thus, be more difficult than in environments with predictable seasonal growth patterns.

Over the long term, climate change can be expected, with high confidence, to result in increasing temperatures, increasing frequency of hot days and warm spells, and an increased intensity of

Table 2. Soil and vegetation characteristics of the southern rangelands as defined in Fig. 1

Data for soils are derived from the Australian Soil Resource Information System https://www.asris.csiro.au/themes/Atlas.html#Atlas_Downloads; vegetation data are from Australia – Present Major Vegetation Groups – NVIS Version 5.1 http://environment.gov.au/fed/catalog/search/resource/details.page?uuid=%7B991C36C0-3FEA-4469-8C30-BB56CC2C7772%7D

Characteristic	Area within the southern rangelands (km^2 × 100)	
	Pastoral	Non-pastoral
Soils – principal profile form (Northcote 1979)		
Duplex with red clay B horizons (Dr)	3719	714
Gradational, calcareous throughout (Gc)	1998	1247
Gradational, not calcareous throughout (Gn)	4422	2557
Uniform, coarse textured (Uc)	3685	10 381
Uniform, medium textured (Um)	5089	3380
Uniform, fine textured, cracking (Ug)	3294	648
Uniform, fine textured, not cracking (Uf)	102	47
Ironstone gravels ≥60% of the total mineral material throughout the profile (KS)	10	272
Gravels other than ironstone ≥60% of the total mineral material throughout the profile; fine earth (<2 mm) matrix, uniform (K-U)	53	918
Other duplex soils	18	74
Not defined in Northcote (1979) (NS)	17	272
TOTAL	22 407	20 510
Vegetation communities		
Acacia forests and woodlands, open woodlands, shrublands	9653	5737
Chenopod shrublands, samphire shrublands and forblands	3018	1543
Eucalyptus open forests, open woodlands, woodlands	1951	1114
Hummock grasslands	2960	7914
Tussock grasslands	2570	577
Mallee woodlands and shrublands, open woodlands and sparse mallee shrublands	473	1069
Other open woodlands	597	761
Other shrublands	569	315
Other	617	1492
TOTAL	22 407	20 524

extreme rainfall events throughout the region. Time spent in drought is also likely to increase throughout the region, although the confidence attached to this prediction is lower. A decline in the annual rainfall is expected with high confidence in the south of the region, but rainfall trends in the north are uncertain (CSIRO and Bureau of Meteorology 2021). A shift in seasonal rainfall distribution, associated with the southward and coastward expansion of the tropical summer rainfall zone could also be expected on the basis of trends since 2000 (White 2016). More extreme temperatures can be expected to directly affect livestock production (Hansen 2009; Johnson 2018) and, indeed, the future habitability of some parts of the region (Gergis 2018, pp. 146, 185). Changes in climatic variables over the period 1991–2007 have been simulated to result in reduced forage production over much of the eastern and southern parts of the region, but with increased production in much of the Western Australian portion, compared with a base line period of 1961–1990 (McKeon *et al.* 2009). Importantly, these changes in forage production reflect an amplification of the corresponding rainfall changes so that any rainfall decline is likely to result in a disproportionately large reduction in forage availability (McKeon *et al.* 2009). Effects of aridity on soil health indices can be of magnitude and sign similar to any grazing effects, suggesting that predicted increases in aridity are likely to reduce soil health potentially as much as changes in grazing intensity, again with negative consequences for pastoral productivity under a changed climate (Eldridge *et al.* 2017).

Intra-regional variability

The heterogeneity of the region with respect to soils, vegetation and climate is reflected in a continuum of primary and potential secondary productivity. In very broad terms, one end is defined by the 'mulga zone' of Western Australia, with AAR generally <200 mm and the widespread occurrence of shallow soils (often <30 cm) underlain by a siliceous hardpan. These soils are widespread in the arid zone of Western Australia (and hence are a substantial component of the region overall) but of very restricted occurrence elsewhere (Hacker 1987). Also located at this end of the continuum are the Nullarbor Plain, with equally low, or lower, rainfall and extensive areas of shallow soil over limestone, and the drier parts of South Australia. At the other end are the higher-rainfall environments on the eastern margins of the region, in south-western Queensland and western New South Wales, with AAR ranging from ~375 to 500 mm where mulga, the signature tree species of the southern rangelands, can form low-open forests or even open forests in the most favourable environments (Nix and Austin 1973). This variability in secondary production potential, reflected in stocking rates ranging from <0.1 dry sheep equivalents (DSE)/ha in the more arid parts to >0.6 DSE/ha on the wetter eastern margins, is a fundamental determinant of the prospects for sustainable land use across the region.

Landscape function

Patchiness of soil and vegetation is a distinguishing feature of semiarid and arid environments in which vegetation is too sparse to allow complete coverage of the ground surface. This patchiness creates, and in part results from, runon–runoff mosaics at small scales that are considered fundamental to the functioning of these landscapes. Water and nutrients are concentrated in vegetated patches that permit both the persistence of perennial vegetation and a higher level of net primary production than would be possible if water were uniformly distributed over the landscape (Noy-Meir 1973).

The 'trigger–transfer–reserve–pulse' framework describes this mode of landscape function (Ludwig and Tongway 1997). In terms of this framework, both 'functional' and 'dysfunctional' landscapes are described. In the former, the patch mosaic is sufficiently fine-grained to promote a tortuous pattern of water flow, resulting in most resources being retained within the local system, whereas in dysfunctional landscapes, where the vegetation pattern has been degraded, the flow is less inhibited, resulting is a loss of resources from the local system (Ludwig and Tongway 1997). Over much of the southern rangelands, maintenance or restoration of functional landscapes, in these terms, will be fundamental to pastoral productivity. Examples are provided by Holm et al. (2003), Holm *et al.* (2005) and Bean *et al.* (2015). Exceptions may include areas where deep sandy soils provide sufficient water storage to support perennial vegetation without the need for local redistribution, because of the 'inverse texture effect' (Noy-Meir 1973), or where landscapes inherently lack a capacity for local concentration of resources, particularly water (e.g. owing to heavy stone cover), and may be subject to seasonal boom–bust cycles that are largely independent of management.

Land administration

Land used for pastoralism in the southern rangelands is administered by State and Territory authorities. Although some areas of freehold title exist, particularly in Queensland, most land is held under various forms of pastoral lease, which may be either 'in perpetuity' or for specified terms, depending on the jurisdiction. Leases typically require lessees to maintain the condition of the land, but failure to do so is often difficult to establish and available sanctions have generally been applied only in clearly unambiguous cases. Pastoralists operating with a freehold title have similar obligations but embodied in different legislation. The State- or Territory-based land administration system is associated with differences among jurisdictions in matters such as lease conditions, monitoring and compliance processes, and biosecurity arrangements relating to pest species and animal health.

Land ownership and land value

Indigenous people now exercise total or partial management control over extensive areas through ownership of pastoral leases, and various forms of land rights, Native Title and Indigenous Land Use Agreements. Their aspirations for land use and their approach to management may differ from that of non-indigenous landowners, embracing Indigenous knowledge, culture and values (Ridges *et al.* 2020).

Apart from the relatively small areas that are held under freehold title, particularly in Queensland, almost all of the land used for pastoral production is held under various forms of pastoral lease. Although the southern rangelands have not seen the move to large corporate entities that characterise the northern pastoral industry, there has been a considerable corporatisation of parts of the region, resulting from the purchase of pastoral leases by mining companies. This trend has been particularly apparent in Western Australia (van Etten 2013). Poor pastoral profitability, particularly of those leases affected by 'invasive native scrub' (INS) in the eastern parts of the region, or other forms of land degradation, has resulted in a rapid turnover of ownership, use of leases for purposes other than pastoral production and lessees who are either absent or engaged in off-property work (URS 2013, 2015).

Nevertheless, land values have increased substantially across the region in recent decades, much more than could be justified by any increase in pastoral productivity, probably reflecting changes in land values elsewhere and potentially creating serious debt-servicing difficulties for recent entrants to the pastoral industry (Bastin and the ACRIS Management Committee 2008). In this respect, the situation in the southern rangelands is comparable to the 'bubble' produced by rising land values in the pastoral industry of northern Australia (Holmes 2015).

Economic status of the pastoral industry

In the eastern parts of the region, particularly in Queensland and New South Wales, closer settlement policies, partially aimed at providing land for returned soldiers after World War 1, resulted in the break-up of large leases and the establishment of many smaller leases, which ultimately proved non-viable. Small lease size has also contributed to land degradation because pastoralists on smaller holdings have tended to adopt higher stocking rates (Table 1) for which the short-term economic benefits are perceived to outweigh the long-term cost of land degradation (MacLeod 1990; Passmore and Brown 1992). The legacy of these policies still persists, even though lease amalgamation, or the combination of several leases into single businesses, has long been a feature of the pastoral industry in these areas, and an objective of government-funded programs (e.g. WEST 2000 Plus in New South Wales and the South-West Strategy in Queensland) in recent decades.

In Western Australia, such closer settlement policies were not adopted but the low productivity of the resource base, noted above, and the effect of well documented land degradation on pastoral productivity (e.g. Payne *et al.* 1987, 1988) have produced a parlous economic situation for the pastoral industry in this part of the southern rangelands. Novelly and Warburton (2012) found that more than half of the 292 pastoral leases in the southern rangelands of this state were non-viable on the basis of their inherent productivity and the 'capacity of the rangeland resources to be managed in an ecologically sustainable manner'. They considered that it was difficult to envisage a future for a substantial portion of leases without further rangeland degradation. However, URS (2013) found that structural adjustment to account for this situation is occurring and that across various subregions of the southern rangelands in Western Australia, the proportion of leases entirely dependent on pastoral activity ranged from 6% to 64% and that non-grazing activity of various types accounted for 30–68% of income. They envisaged a 'new era' for Western Australian rangelands in which businesses would be multi-faceted and the conduct of pastoral enterprises would not necessarily be a prerequisite for lease-holding of land within the region. Similar sentiments had previously been expressed by Fargher *et al.* (2003) and Hunt (2003) in relation to the rangelands nationally. The nature of this transition in the Western Australian portion of the southern rangelands has been summarised by van Etten (2013), noting that in some subregions, extensive contiguous tracts now exist with no or reduced domestic stocking, which can contribute to broad scale conservation management and restoration objectives. Indeed, some former pastoral leases have been specifically purchased by public or private agencies for this purpose.

Rangelands as socio-ecological systems

Rangelands and the industries and communities dependent on them constitute human-environmental, or socio-ecological, systems. Reynolds *et al.* (2007) argued that in drylands, such systems are characterised by a unique set of features (a syndrome) that include climatic variability and unpredictability, sparse populations, distant markets and remote governance. They proposed the Dryland Development Paradigm, comprising five basic principles, to analyse changes in these systems. Local environmental knowledge is seen as fundamental in mediating the interactions between the human and environmental subsystems, which mediates their co-evolution. Stafford-Smith *et al.* (2007) found that these principles were all reflected in the degradation episodes in the Australian rangelands described by McKeon *et al.* (2004) but considered that strictly local environmental knowledge alone may be insufficient to ensure sustainable management. They considered that learning systems based on a wider community are required which combine local knowledge, formal research and institutional support. Strictly local learning is impeded by variability in both environment and social subsystems, and the extended time frames over which 'slow variables' (such as climate change, multi-decadal climate cycles and changes in landscape function) operate. This feature of the southern rangelands is an important part of the rationale for our attempt to distil management principles from the knowledge held outside local pastoral communities. However, application of these principles to achieve sustainable land use across the region is likely to be influenced by the extent to which governance arrangements for natural resource management reflect the principles of polycentricity and subsidiarity embedded in the concept of adaptive governance advocated by Marshall and Stafford-Smith (2010).

Emerging land uses

Carbon sequestration

Gammage (2012) has collated numerous references to the open, park-like appearance of extensive areas of southern Australia at the time of European settlement, attributed to Aboriginal burning practices. Such practices were probably responsible for the preservation of extensive areas of open woodland in vegetation types dominated by *Acacia* and *Eucalyptus* species in the semiarid eastern parts of the southern rangelands, defined by Harrington *et al.* (1984*a*, 1984*b*) as 'semiarid woodlands' (although a contrary view has been expressed by Silcock and Fensham 2019).

The encroachment of INS in the semiarid woodlands under traditional pastoral management renders these environments well suited to the development of an alternative land use that provides an economic return from carbon sequestration (Moore *et al.* 2001). This potential is best developed in south-western Queensland, particularly the 'eastern sector' of the mulga lands recognised by Nix and Austin (1973), and in north-western New South Wales. Considerable areas within the semiarid woodlands have been devoted to carbon sequestration projects in recent years under either the 'avoided deforestation' (AD) or 'human induced regeneration' (HIR) methodologies of the Commonwealth Government's Emissions Reduction Fund. The former (AD), involves landholders foregoing the right to clear native vegetation previously approved under a certified vegetation management plan; HIR projects involve the promotion of even-aged stands of native forests on land where development of forest cover has previously been actively suppressed. Cockfield *et al.* (2017) noted that at least 115 such projects, covering 1.8 million hectares, had been contracted to that time in the Cobar Peneplain and Mulgalands regions of New South Wales alone. The government investment in these projects was estimated at approximately AU$590 million. The current distribution of abatement projects (ERF 2020) indicates that comparable areas had probably been contracted in south-western Queensland. Since payments for carbon sequestered are generally loaded towards the early years of HIR projects, the value of carbon sequestration over the medium term is likely to be significant relative to the value of grazing (estimated above at AU$1.4 billion in 2016–17 for the southern rangelands in total; see footnote[2]).

The extent to which carbon sequestration will form a basis for changed land use in other parts of the southern rangelands is questionable. Garnaut (2019, p. 150) suggested a sequestration potential of ~250 million tonnes of CO_2-equivalent per annum in the semiarid rangelands. Outside the areas discussed above, this potential is likely to be realised mainly on the fringes of the wheat–sheep zone in South Australia and Western Australia, as these boundaries contract under a warming and drying climate. Even though landholder interest and project initiation have been considerable outside these fringe areas, especially in the mulga zone of Western Australia (Baumber *et al.* 2020), it is doubtful that these more arid parts of the southern rangelands will be capable of meeting the definition of forest cover required by the HIR methodology. The absence of approved plans for vegetation clearing in the more arid parts of the region will, likewise, prevent the implementation of carbon sequestration projects under the AD methodology.

Exclusion of both fire and grazing is generally required to maximise long-term (110 years) carbon sequestration in HIR projects, although over the 25-year commitment of many projects, carbon sequestration would be little affected by light grazing (20% utilisation of available forage; Howden *et al.* 2001). Even over longer terms, carbon sequestration might be little affected by grazing that is managed to ensure that germination and establishment of new cohorts of mulga or other species is not inhibited.

Ecosystem services

Payment for ecosystem services through a range of market-based instruments is an emerging alternative land use that can motivate land managers to conserve or manage land to achieve environmental or public benefits (Higgins *et al.* 2014; Ansell *et al.* 2016). Examples of these schemes in the southern rangelands include the 'Pastoral Stewardship Incentive Pilot' in South Australia (Wilson and Freebairn 2017) and the Enterprise Based Conservation project conducted under the West 2000 Plus Commonwealth–State Rural Partnership Program in western NSW (URS 2015). In the latter scheme, pastoralists could choose to receive financial incentives either for managing particular areas of land for conservation objectives, or for maintaining ground cover as close as possible to agreed targets (Hacker *et al.* 2010).

Whereas these schemes have applied to only a small proportion of grazing land in the southern rangelands, the growing recognition of the importance of biodiversity conservation and other components of natural capital in agricultural landscapes is likely to see markets for ecosystem services increase in the future. However, for such mechanisms to be effective in delivering public benefits, they will need either to be assured of long-term funding through incorporation into government policy and funding arrangements, or be able to operate profitably in the commercial market as proposed by Wilson *et al.* (2020) in relation to custodianship of wildlife on private land to support both diversified incomes for landholders and conservation. They will also require credible, landscape-scale monitoring methodologies.

Potential for renewable energy production

Garnaut (2019) has drawn attention to the major economic opportunities provided by Australia's high quality solar and wind energy resources, derived from extensive land areas, favourable climatic regimes and limited competitive land uses. The southern rangelands would, thus, appear to be ideally suited to industries based on renewable energy generation. Although distance from demand sources may favour less remote areas for development of small and medium scale projects utilising legacy grids, the transmission technology available to mega-scale projects should mean that potential for large renewable energy farms should exist throughout much of the region (Boulaire 2021).

Impacts of pastoral land use

Initial optimism of pastoral settlement

As in many cases of settlers moving into new environments, the capacity of the southern rangelands to support pastoral production was often initially overestimated, an assessment sometimes exacerbated by 'long periods of good seasons' (Fyfe 1940, p. 20) in the early years of settlement before a major drought. This, combined with the limited availability of water supplies before the advent of heavy machinery for dam construction, and polythene pipelines for water distribution, often resulted in excessive numbers of animals being carried on individual watering points and rapid and severe degradation of the surrounding area (e.g. Osborn *et al.* 1932, cited in Andrew and Lange 1986; Nicholson 2017, pp. 35–36). In addition, the desire of governments in some states to ensure that pastoral leaseholds were taken up by genuine settlers and that pastoral development proceed as rapidly as possible, combined with optimistic assessments of carrying capacity, led to the imposition of lease conditions that no doubt contributed to land degradation.

Suitability of land for traditional pastoral use

Since climatic conditions in the southern rangelands do not require stock to be removed on a regular basis (e.g. due to very cold winters), the grazing system is predominantly sedentary. Grazing has traditionally continued year-long, with stocking rate being the major variable under management control, and stock being removed from their paddock only for annual operations such as shearing, or when pastures could no longer support them, rather than for pasture management purposes. This traditional system of management is arguably incompatible with the ecology of some parts of the southern rangelands.

The incursion of INS over extensive areas of the semiarid woodlands has been noted above. Contributing factors are generally considered to have been the changed fire regime resulting from the cessation of Indigenous burning, the European tendency to supress wildfire, consumption of the grassy fuel by livestock, and the weakening or removal of the competition for establishing shrub seedlings previously provided by perennial grasses (Harrington 1991). This latter factor is probably of increased importance following the reduction of rabbits, which 'consume almost all seedlings of these [semiarid zone tree] species'; Wilson *et al.* 1992, p. 10) by biological control methods from the 1950s. Witt *et al.* (2009) demonstrated considerable variation in multi-decadal woody cover change among sites, land types and rainfall zones in south-western Queensland, so the generality of this model may be questioned. Nevertheless, since traditional pastoral management provides limited opportunities to rest country to build adequate fuel loads for management burning, to implement burns over extensive areas when seasonal conditions are favourable, or to maintain perennial grasses, it is arguably incompatible in many situations with maintenance of the productive grassy state that was attractive to early pastoralists. We would argue that this incompatibility remains despite any contribution to INS encroachment that may have resulted from increased atmospheric CO_2 concentrations (Polley *et al.* 1997; Ward 2010; Donohue *et al.* 2013), whose correlation with global woody plant increases was considered by Archer *et al.* (1995) not to represent cause and effect.

Where palatable perennial shrubs allow livestock to be retained under dry conditions, there may be another mismatch between ecology and traditional pastoral management. Under these circumstances, excessive pressure may be placed on perennial grasses, especially where these were originally sparse as, for example, on the extensive areas of shallow hardpan soils in the mulga shrublands of Western Australia. Beeton *et al.* (2005, cited by Silcock and Fensham 2019), considered drought feeding of palatable mulga scrub to be a major factor contributing to degradation of mulga communities in the eastern part of the region. Long-lived perennial grasses were probably important for animal production, given the nutritional importance of green leaf (Freudenberger *et al.* 1999), but their retention has proved difficult when browse permits the prolonged retention of livestock under adverse seasonal conditions.

In chenopod shrublands, there is a natural ecology that is arguably more compatible with sedentary grazing than those situations described above. In these environments, inter-shrub growth is composed of annual herbs and annual or short-lived perennial grasses, the species mix depending on the seasonal incidence of rainfall. Since this ephemeral growth is preferred by livestock when available (Pahl 2019*a*) there is an inherent capacity in these communities to provide some natural rest from grazing for the major perennial elements. For this reason, Wilson (1979) considered that 'controlled continuous grazing', at stocking rates that avoid complete defoliation of the shrubs, was the best management option for saltbush (*Atriplex vesicaria*) communities in south-western New South Wales. Nevertheless, continuous grazing even at conservative stocking rates leads to some long-term depletion of the perennial shrubs (Andrew and Lange 1986; Watson *et al.* 1997).

Although modern pastoral management is often superior to traditional practice, incorporating for example resting of paddocks and containment feeding under drought conditions, the land and the pastoral industry still suffer the legacy of the incompatibilities described above.

Impact of pastoralism on land condition

Six major degradation events since 1890, in the sense of depletion of perennial vegetation and soil erosion under conditions of drought and high grazing pressure, have been described by McKeon *et al.* (2004) in the southern rangelands. Incursion of INS into previously 'open' areas in the semiarid woodlands, associated with a period of high rainfall, is described as a seventh major 'degradation' event.

Noble *et al.* (1996) summarised the various reports on the condition of the grazed southern rangelands available at that time. The proportion of regional survey areas in Western Australia, South Australia and Queensland considered to be in 'Poor' or 'C' (degraded; Tothill and Gillies 1992) condition classes ranged from 20% to 42%. However, the extent of degradation was highly variable among survey regions and vegetation types, and methodologies differed among surveys, so that generalisation is difficult. Survey results from the Western Division of New South Wales reported the extent of particular types of degradation rather than condition classes. Encroachment of INS was considered 'moderate' or 'severe' over 37.6% of the division, whereas 'moderate' or 'severe' sheet/rill erosion, gully erosion and scalding were reported for 0.1%, 8.9% and 18.6% of the region respectively.

A common finding of regional surveys is that the level of degradation tends to be greatest in land types or vegetation communities with the highest potential for pastoral production (Noble *et al.* 1996). The effect of degradation on pastoral productivity at landscape scale could thus be greater than suggested by the figures above. Several studies in the southern rangelands have found that loss of palatable shrubs, associated with enhanced growth of ephemeral species, does not reduce animal production under reasonable seasonal conditions at commercially realistic stocking rates (Leigh *et al.* 1968; Wilson and Leigh 1970; Graetz 1986; Wilson and MacLeod 1991; Holm *et al.* 2005), but a disproportionate effect of degradation of the more productive land is likely to be manifest under poor seasonal conditions.

Across the southern rangelands in New South Wales, South Australia, Northern Territory and Western Australia indicators of both landscape function and critical stock forage were stable or increased for a majority of sites from the early 1990s to 2005 (Bastin and the ACRIS Management Committee 2008, figs 3–7 and 3–12 respectively). When these gross changes were adjusted for seasonal conditions, up to 20% of sites (depending on bioregion) showed an improvement in landscape function despite poor seasonal conditions, whereas a somewhat smaller percentage of sites showed a decrease in landscape function under favourable seasonal conditions (fig. 3.8 in Bastin and the ACRIS Management Committee 2008). A similar picture emerged for the various indicators of critical stock forage (fig. 3–13 in Bastin and the ACRIS Management Committee 2008). These counterintuitive trends, observed on a minority of sites, suggest that both beneficial and non-beneficial impacts of management are reflected in the data.

More recent survey data from the West Australian Rangeland Monitoring System showed that in the upper and lower southern rangelands of that state, respectively, vegetation cover for 15% and 43% of the area of the most productive pasture types had decreased or not improved between 2009 and 2019 (Department of Primary Industries and Regional Development 2019). The average density of pastorally desirable shrubs had decreased across both subregions, following widespread increases in density, canopy area and species richness, under generally favourable seasonal conditions, reported earlier by Watson *et al.* (2007). Continuing decline in vegetation condition was considered highly likely if grazing pressure was maintained or seasonal conditions deteriorated (Department of Primary Industries and Regional Development 2019).

Trends in range condition indicators are today variable in space and time. They reflect overwhelmingly the influence of seasonal conditions, but with management, nevertheless, able to exercise a discernible effect, either by allowing seasonal responses to be expressed or by inducing counterintuitive trends. It is not possible to discern any overall directional trend, and broad generalisations about the state of 'the rangelands', or their trend, should be avoided. Furthermore, regional assessments such as those reported above may be insensitive to degradation processes operating in restricted parts of the landscape (e.g. Pringle and Tinley 2003; Pringle *et al.* 2006), which will be important for individual land managers.

Impact of pastoralism on biodiversity

Since European settlement, drought, habitat degradation by introduced herbivores and predation by feral cats and foxes has resulted in the extinction of 11 medium-sized arid-zone mammal species and a dramatic reduction in the range of many others (Morton 1990; Lunney 2001; Silcock and Fensham 2019). Woinarski and Fisher (2003) suggested that most mammal losses from the semiarid rangelands occurred between the 1850s and 1880s. In the 19th and 20th centuries, bounties were paid as an incentive for population control of native fauna including dingos, kangaroos, wallabies, bandicoots, bettongs, emus, eagles and kites (Hrdina 1997). The campaign against the dingo was successful in reducing their populations across large tracts of the arid zone (e.g. Glen and Short 2000).

Rangeland birds, reptiles and amphibians have been less affected than mammals. Although range and abundance of many arid zone bird species, particularly ground-nesters and those associated with riparian habitats, have declined since colonisation (Reid and Fleming 1992), Morton (1990) reported that no species has become extinct. Saunders and Curry (1990) suggested that there is little to indicate that the present-day status of any bird species in the Australian arid zone is changing rapidly. Increasing, decreasing and stable trends have been identified among 49 rangeland bird species over the period 1999–2006 (Cunningham *et al.* 2007). Causal factors were unknown but seasonal variation appeared to be involved for many species. No desert-dwelling reptile or amphibian has become extinct (Morton 1990) and there is no evidence that the abundance of any reptiles has declined (Wilson and Swan 2017).

Despite this, the abundance of native fauna has been reported to be greater under light than heavy grazing intensity (James 2003; Read and Cunningham 2010), and Haby and Brandle (2018) found that the gradual passive recovery of small mammal and reptile assemblages in the Flinders Ranges in South Australia was facilitated by the removal of livestock in open *A. aneura* woodland in fair condition, but not in degraded chenopod shrubland. In contrast, no significant difference in animal richness or abundance was reported with differences in grazing intensity in a comprehensive review of Australian literature by Eldridge *et al.* (2016).

The impact of grazing, or pastoral development generally, on biodiversity could be expected to be non-uniform, associated with gradients of grazing pressure around watering points. Although localised effects on biodiversity may be observed, the proliferation of artificial waters across the southern rangelands (Hacker and McLeod 2003; Watson *et al.* 2005, cited by Bastin and ACRIS Management Committee 2008, pp. 56–57) means that few areas today would be unaffected. Studies of the response of animal species to these gradients indicate that some increase in abundance with increasing grazing pressure, others decrease and others are unresponsive (Landsberg *et al.* 1997).

Although some plant species have been shown to be negatively affected by pastoralism and, in some instances, have been eliminated from heavily grazed areas (Landsberg *et al.* 2003), most species remain widespread and common and, with the exception of some species endemic to artesian mound springs subject to substantial drawdown (Silcock and Fensham 2019; Powell *et al.* 2015), few have declined so as to be considered rare at the landscape scale (Silcock *et al.* 2014; Silcock and Fensham 2019). Overall, the drier parts of Australia have been much less modified by European settlement than have more arable regions, and the adaptation of the flora to drought has probably conferred some resilience to exotic herbivores (Silcock *et al.* 2014).

Nevertheless, severe grazing pressure in the past has caused transitions that are still apparent in landscapes today. Some shrub species, for example, have increased where populations of grazing-sensitive species such as *Atriplex vesicaria* have been reduced by over-grazing (Tiver and Andrew 1997), sometimes to the point of local extinction because of a lack of recruitment (Hunt 2001). Under current land management, recruitment of numerous dryland shrubs and trees is limited or even prevented so that some of the more restricted species are at risk of extinction as older plants senesce (Tiver and Andrew 1997; Denham and Auld 2004).

Grazing gradient studies have shown, as for faunal taxa, that some plant species increase in abundance with increasing grazing pressure, others decrease, and some appear to be unresponsive (Landsberg *et al.* 1997, 2003). Díaz *et al.* (2007) reported an increase in the proportion of annual, prostrate and unpalatable species with increasing grazing intensity. At low grazing intensities, impacts on plant diversity are minimal (Fensham 1998; Fensham *et al.* 2014), although changes in composition are often observed (Fensham *et al.* 2010).

A comprehensive picture of responses of rangeland ecosystems to plant invasions is not available (Grice 2006). Of 17 grass species identified by van Klinken and Friedel (2017) as 'high-impact' environmental weeds in Australia, only *Cenchrus ciliaris* (buffel grass) and *C. setiger* (birdwood grass), introduced as pasture species suitable for semiarid environments, have made significant inroads in the southern rangelands (Miller *et al.* 2010). Buffel grass has most commonly colonised badly degraded and eroded areas in the more fertile parts of the landscape and is considered 'naturalised' in most Australian rangelands, except South Australia where it remains a 'declared' plant (*Landscape South Australia Act* 2019). These species place native ecosystems at risk through competition (e.g. Franks 2002) and elevated fire frequency and intensity (Miller *et al.* 2010). Weeds of National Significance in the southern rangelands include various opuntioid cacti (*Austrocylindropuntia*, *Cylindropuntia* and *Opuntia* species), which are widespread in both western and eastern parts of the region (Hosking *et al.*1988; Western Australian Herbarium 1998). Ward's weed (*Carrichtera annua*) has invaded extensive areas of the southern rangelands since its accidental introduction to South Australia in the early 1900s, particularly on calcareous soils in areas of winter-dominant rainfall (Cooke *et al.* 2011).

Impacts of pastoralism on the 'weak points' in spatially and temporally variable rangeland systems (Stafford-Smith and McAllister 2008) may well have disrupted evolutionary processes in ways that are not yet well defined. Nevertheless, care should be taken not to accept uncritically the conventional narratives about rangeland degradation (Silcock and Fensham 2019). There is no evidence that any plant species has become extinct as a result of pastoral settlement (Silcock *et al.* 2014; Powell *et al.* 2015), and most faunal taxa appear to have been little affected, in stark contrast to the 'catastrophic' record of mammal extinctions in the arid and semiarid zones attributable primarily to introduced predators (cats and foxes) rather than pastoralism (Silcock and Fensham 2019).

Key issues, principles and guidelines for sustainable pastoral land use

In this section, we review what we consider to be the key issues that must be addressed to achieve sustainable pastoral land use in the southern Australian rangelands and formulate this understanding,

Table 3. Principles and guidelines for sustainable pastoral management in the southern rangelands

Principle 1. Manage grazing within a risk management framework based on the concept of tactical grazing

Guideline 1.1. Obtain the best available estimates of the DSE ratings for sheep (Merinos and Dorpers), goats, cattle and kangaroos and monitor total DSE over land units.

Guideline 1.2. Develop an estimate of the carrying capacity of the property for the current enterprise and current land condition, including the availability of browse, and express this as a benchmark value of DSE days/ha per 100 mm of (average) annual rainfall.

Guideline 1.3. Estimate prospective short-term grazing capacity based on seasonal climate forecasts and the carrying capacity benchmark (or some alternative approach such as a grazing chart).

Guideline 1.4. Develop land management objectives (considering both biodiversity and production issues) for all management units, and associated grazing management strategies, defined in terms of variables that can be monitored as a basis for action, such as ground cover and utilisation level of key species.

Guideline 1.5. Establish monitoring systems that will provide the input required for tactical grazing responses and for assessing progress towards management objectives (these will be different systems, based on different measurements or observations).

Guideline 1.6. Develop 'trigger points' appropriate to the local environment to assist with management decision making.

Guideline 1.7. Manage non-domestic grazing pressure by appropriate and socially acceptable means (e.g. non-commercial culling of kangaroos by professional shooters, trapping and sale of unmanaged goats with no release of animals of no commercial value).

Principle 2. Develop infrastructure to allow best management of both domestic and non-domestic grazing pressure

Guideline 2.1. Use fencing specifications that provide the most cost-effective control of non-domestic grazing pressure.

Guideline 2.2. Fence to land type as far as possible where new or replacement fencing is being erected.

Guideline 2.3. Establish infrastructure at watering points that allows efficient mustering of livestock and humane control of access to water by non-domestic herbivores.

Principle 3. Incorporate management of invasive native scrub (where appropriate) into overall property management on an ongoing basis

Guideline 3.1. Monitor the presence of woody seedlings under seasonal conditions likely to produce mass germination and establishment (sequences of good seasons).

Guideline 3.2. Keep open areas open.

Guideline 3.3. Determine the likely long-term benefit of a successful control program so as to estimate the money that could be spent on control; ensure consideration of follow-up treatment and TGP management in treated areas.

Guideline 3.4. Consider the potential of areas susceptible to encroachment to contribute to income and enterprise diversification by entry into a carbon sequestration project.

Principle 4. Seek to enhance biodiversity conservation at landscape scale

Guideline 4.1. Protect areas remote from water from new water development.

Guideline 4.2. Exercise stewardship of sensitive habitats (e.g. mound springs or rock wallaby habitat).

Guideline 4.3. Control foxes (and if possible feral cats) by active baiting programs aimed primarily at improved animal production, but with the secondary benefit of conserving native fauna.

Guideline 4.4. Consider the biodiversity implications if management objectives are likely to be compromised under a tactical grazing regime.

Guideline 4.5. Consider the potential for management of biodiversity or provision of ecosystem services to attract stewardship payments for delivery of public goods.

following the format of Hunt *et al.* (2014), in terms of principles and guidelines for sustainable pastoral management (Table 3).

Carrying capacity and stocking rate

While of little value for day-to-day stocking decisions, knowledge of the estimated carrying capacity (see Table 1) of a property *in its current condition* is fundamental to sustainable management because this establishes the centroid around which actual stocking rates can be expected to fluctuate. It also provides a measure of productive potential, both absolute and relative to other properties, which will be important in dealing with financial institutions. Carrying capacity estimates for all pastoral leases in the southern rangelands have been compiled by land administration authorities on the basis of a range of methods (e.g. Condon 1968; Condon *et al.* 1969; Johnston *et al.* 1996*a*, 1996*b*; Hamilton *et al.* 2008), but often do not reflect the *current* condition of the property. In practice, it may be necessary for landholders to develop their own estimate of carrying capacity on the basis of historical stock records, a critical assessment of the condition of the land that has resulted from historical management, and any other local knowledge available. Because carrying capacity needs to be expressed in terms of some equivalence scheme (Table 1), information is required concerning the equivalence ratings for the species, domestic and non-domestic, that graze on the property (Guidelines 1.1 and 1.2).

Despite the acknowledged importance of stocking rate for animal production, the classical relationships defined by Jones and Sandland (1974) are often difficult to detect in large semiarid and arid zone paddocks because of spatial and temporal variability of forage supply (Roshier and Barchia 1993; Ash and Stafford-Smith 1996; Roshier and Nichol 1998; Freudenberger *et al.* 1999), and often the presence of substantial numbers of non-domestic herbivores (Hacker *et al.* 2019*a*). Numerous studies in the southern rangelands (e.g. Wilson and Leigh 1970; Wilson 1991*a*; Roe and Allen 1993; Roshier and Barchia 1993; Freudenberger *et al.* 1999; Holm *et al.* 2005) have demonstrated the overriding importance of seasonal variation in determining both animal and vegetation responses. Generally, the order of influence for almost any response variable is therefore as follows: (1) seasonal conditions, (2) stocking rate and (3) management system.

Some formal studies in the southern rangelands, and much anecdotal evidence, indicate that 'conservative' stocking, which includes both moderate stocking rates and early response to developing drought conditions, gives the best outcomes both ecologically and economically in this highly variable environment (Hacker *et al.* undated; Morrissey and O'Connor 1989;

Woods 1992; Buxton and Stafford-Smith 1996; Stone 2004; Stafford-Smith and McAllister 2008). Over the long term, benefits of conservative stocking are achieved through higher production per head, improved reproduction rates, reduced production costs particularly in dry years, and opportunities to improve both the genetic potential of the herd/flock and land condition. Similar conclusions have been reached by studies outside the southern rangelands in Australia (e.g. Rickert 1996; Landsberg *et al.* 1998) and overseas (e.g. Holechek *et al.* 1999; Higgins *et al.* 2007; Fynn *et al.* 2017).

A method of calculating conservative stocking rates, proposed by Hacker and Smith (2007), uses a benchmark (BM) value of DSE days per ha/100 mm of average annual rainfall (DDH/100 $mm_{(BM)}$), derived from long-term average annual pasture growth and a 'safe' utilisation factor derived from Johnston *et al.* (1996*a*). In practice, the numerator of this ratio, a measure of carrying capacity, may need to be derived more subjectively, as noted in the discussion above. Once established, the BM can be used proactively to predict future conservative stocking rates on the basis of seasonal climate forecasts for the next 3 months (Guideline 1.3). However, careful monitoring of utilisation levels achieved in the field is still required. Alternatively, use of a grazing chart that records the stocking history of a paddock, and thus allows the effective stocking rate to be subjectively related to the impact on measures of land condition (e.g. utilisation of preferred species or ground cover), could be used to estimate conservative stocking rates retrospectively.

Even at low levels of grazing, impacts on ecosystem function, structure and composition are largely negative, and more pronounced in dry, lower-productivity environments (Eldridge *et al.* 2016, 2017). Accepting that some impact of pastoral use is inevitable, such findings reinforce statements made elsewhere in relation to Australian rangelands that 'getting the stocking rate right' is the major management issue (Stafford-Smith *et al.* 2007) and that stocking rate is 'the most critical aspect of livestock grazing' because of its profound effects on livestock production, financial performance and land condition (Hunt *et al.* 2014). We concur with these statements in relation to the southern rangelands while acknowledging that management system, i.e. the pattern of grazing and resting imposed on particular paddocks, or the property overall, can have important additional effects (see below).

Grazing system

In large paddocks at low stocking rates, livestock do not graze the landscape uniformly (Fuls 1992; Barnes *et al.* 2008). Selective grazing under the traditional continuous grazing model can result in over-utilisation and a loss of perennial grasses and other desirable species (Norton 1998), thereby increasing the risk of land degradation and associated negative impacts on production.

Grazing systems that incorporate periods of rest between grazing events have been widely promoted as improving both production and environmental sustainability (e.g. Savory 1983; McCosker 2000; Teague *et al.* 2008). Numerous systems have been developed, defined by the number of paddocks and number of herds/flocks, their dependence on vegetation dynamics, and the timing, duration and frequency of grazing and rest periods (di Virgilio *et al.* 2019). Included are systems designated as seasonal, deferred, rotational, short duration, holistic and cell grazing. In these systems, grazing smaller areas at higher stock densities can increase the uniformity of grazing by reducing selective and patch grazing, and increasing grazing pressure on species that would not otherwise be utilised (Norton 1998, 2003). In addition, rest allows vigour of palatable species to be maintained as they can recover between grazing events (Norton 1998). However, excessive subdivision, and rapid movement of animals among paddocks, may also deny their access to the functional heterogeneity that can be beneficial to health and production (Fynn *et al.* 2017). In similar vein, Fuhlendorf *et al.* (2017) contended that grazing management that aims to promote uniform, moderate grazing across the entire landscape fails to promote the spatial and temporal heterogeneity that enhances biodiversity in agricultural landscapes. These authors put the case for large continuous tracts of rangeland, not closely subdivided, to enable disturbance processes to interact with inherent heterogeneity, so as to form multi-scaled mosaics capable of providing multiple goods and services.

The production and sustainability benefits of rotational grazing strategies have long been debated (e.g. Briske *et al.* 2008, 2011; Teague *et al.* 2013). A global meta-analysis of 176 studies incorporating periods of planned rest (McDonald *et al.* 2019*a*) reported increased ground cover and animal production per hectare under grazing systems that include rest, with benefits generally increasing with longer periods of rest relative to grazing. However, incorporation of rest did not result in significant differences in biomass, plant diversity or animal production per head. In contrast, another recent global review of grazing strategies in rangelands did not find statistical evidence of improved sustainability under rotational grazing strategies (di Virgilio *et al.* 2019). Similarly, reviews by Hawkins (2017), Briske *et al.* (2008) and Holechek *et al.* (2000) also reported no benefits of holistic or rotational grazing for production or sustainability.

However, producers often claim considerable benefit from non-continuous grazing systems. Differences between producers' experience and the scientific evidence outlined above are in part attributable to the short duration and small spatial scales at which experimental studies are typically conducted, along with confounding by stocking rates and inflexible, experimental grazing treatments (Teague *et al.* 2013). In particular, more uniform utilisation of the landscape owing to the subdivision that usually accompanies rotational grazing can allow higher stocking rates to be maintained (Norton 1998, 2003), realising benefits for commercial producers that are not evident at experimental scales.

Within the southern rangelands, few studies have compared rotational and continuously grazed systems and all have been conducted in the semiarid rangelands of New South Wales. Total ground cover was consistently reported to be greater under rotational grazing (Alemseged *et al.* 2011; Waters *et al.* 2017; McDonald *et al.* 2018). In addition, rotational grazing was reported to result in greater total standing dry matter (Alemseged *et al.* 2011), greater plant diversity but lower invertebrate diversity (Waters *et al.* 2017), and comparable or greater plant diversity and richness (McDonald *et al.* 2019*b*). No differences in soil organic carbon, landscape function, soil properties, plant evenness and turnover, or plant functional diversity were reported (Alemseged *et al.* 2011; Orgill *et al.* 2017; Waters *et al.* 2017; McDonald *et al.* 2018, 2019*b*). Studies in other lower-rainfall regions of Australia have also reported a range of ecological benefits from rotational grazing (Sanderman *et al.* 2015; Bowman *et al.* 2009; Sanjari *et al.* 2008, 2016). However, in southern New South Wales, Tupper (1978) found few differences in plant and animal responses between deferred and continuous grazing systems.

It seems axiomatic that non-continuous grazing systems that involve calendar-based movements of livestock are not suited to the highly variable rainfall environment of the southern rangelands. At the same time, rainfall variability in the region is such that continuous grazing (at appropriate stocking rates) could be sustained without ecological damage for periods considerably longer than the graze periods typical of formal rotational grazing systems. In this situation, a tactical approach to grazing should be preferable to either a specific grazing system or continuous stocking, and has been advocated by Hacker and Hodgkinson (1996), Campbell and Hacker (2000) and Fisher *et al.* (2005) (Principle 1). Further, the demonstration by Windh *et al.* (2020) that fluctuations in market conditions can outweigh production difference among grazing systems in terms of net returns cautions against commitment to any rigid grazing management philosophy.

Four key steps to tactical grazing management, as recommended by Campbell and Hacker (2000), include the following: (1) setting a management objective for each management unit (broadly, either maintenance or restoration of resource productivity, although biodiversity issues should also be considered), which may entail changing pasture composition to favour palatable perennials or reduce weeds, or increasing plant density or ground cover (Guideline 1.4); (2) determining a strategy, essentially a statement of management principles, to achieve the desired objective in each paddock, including threshold levels of pasture utilisation and ground cover, or more specific guidelines for timing, duration and frequency of rest; specification of the conditions for management burning could also be included, as could the use of landscape rehabilitation techniques such as water ponding (Guideline 1.4); (3) implementing the strategy on a day-to-day basis (i.e. tactically) in response to changing seasonal conditions and animal requirements; and (4) monitoring results to ensure objectives are being achieved, or to revise them if necessary (Guideline 1.5).

Grazing conducted according to this framework recognises that the way in which the landscape has been 'conditioned' will determine its response to any particular event. The levels of ground cover and soil seed pools, for example, will determine the response to a high rainfall event, and the response to a period of water deficit will be determined by the level of defoliation (Hacker *et al.* 2006*a*). It represents a 'continuous' rather than 'event-driven' model of grazing management, which Watson *et al.* (1996) considered more appropriate for managers seeking to maintain or restore productive landscapes, and will have the effect of promoting favourable responses to seasonal opportunities while minimising the impact of seasonal hazards.

Two types of monitoring are implied by this approach, namely, short-term monitoring of critical thresholds or other guidelines to inform tactical responses, and long-term monitoring of variables that reflect the objectives (Guideline 1.5). Bowman *et al.* (2009) provided an example of the successful application of this basic approach. The short- and long-term monitoring requirements would be assisted by the development of technology-based monitoring capabilities (Nielsen *et al.* 2020).

Implementation of tactical grazing will be assisted by the identification of local 'trigger points', i.e. calendar dates beyond which stocking decisions should not be delayed in the hope of improved seasonal conditions, or additional growth to support increased stocking (Guideline 1.6). Such trigger points have been identified for numerous locations in western New South Wales by Hacker *et al.* (2006*b*), but elsewhere will need to be devised from local knowledge and rainfall records.

In practice it may not always be feasible to implement the strategy in each management unit at all times. All stocking decisions have implications for the economic welfare of the business, and the seasonal or market risk to which the business is exposed, as well as the ecological condition of the land. Balancing these requirements may mean that the 'ideal' management response specified by the strategy is not always feasible or chosen. However, using the tactical grazing approach will allow managers to make informed decisions on how best to move towards their management goals (Campbell and Hacker 2000), and better appreciate the longer-term implications of short-term management decisions. The tactical grazing concept thus entails a risk management framework within which graziers will find their own point of balance in an informed way (Principle 1).

Tactical grazing as described above has similarities to holistic management or cell grazing, especially if herds or flocks are combined into large units and most of the landscape is unstocked at any time. Both, for example, stress the setting of management objectives and eschew calendar-based movements. However, unlike these approaches, tactical grazing does not stress the importance of animal impact or herd effect, aimed at breaking up capped soil surfaces and facilitating local infiltration of rainfall, and the intensive subdivision that it often associated with such emphasis. As outlined previously, local redistribution of resources is considered an essential feature of functional arid and semiarid ecosystems, and although animal impact may have application in some specific situations, it is not considered a fundamental management principle (Hacker 1993).

Total grazing pressure

In the southern rangelands, domestic livestock graze alongside populations of native and feral herbivores which contribute substantially to the total grazing pressure (TGP). The non-domestic herbivores found almost ubiquitously throughout the region include kangaroos, 'unmanaged goats' (see Table 1) and rabbits (although the latter are not widespread in the arid zone of Western Australia), and, in some areas, feral pigs, donkeys, horses and dromedary camels. The widespread provision of more or less permanent stock waters, suppression of the major predator, the dingo (particularly within the 'dog-proof' fence), and, in some areas, favourable modification of vegetation by livestock has contributed to the increase in both native and feral animals in the southern rangelands (Hacker *et al.* 2019*a*).

At times, it has been shown that less than half the (vertebrate) herbivory in the southern rangelands (defined in this case as areas below the Tropic of Capricorn) is managed by pastoralists (Waters *et al.* 2018); these authors estimated that, in total, 28.93 million DSE were currently grazing the region, of which

15.57 million (approx. 54%) were macropods and goats, and 13.36 million (approx. 46%) were livestock. These figures are consistent with a national survey of landholders and natural resource management service providers who agreed that, on average, 40–50% of the total demand for forage is due to non-domestic animals, and that these levels are at least double what would be desirable from pastoral and land management perspectives (Atkinson *et al.* 2019). Waters *et al.* (2018) estimated that kangaroos represent 83% of the unmanaged grazing pressure, or ~44% of TGP.

Effective management of TGP is thus critical to sustainable management of the southern rangelands (Guideline 1.7). Where unmanaged grazing pressure has been controlled and/or long periods of rest are included in the grazing system, increases in perennial ground cover of 9–15% have been reported (Waters *et al.* 2017). Management of kangaroos is of central importance (a) because they represent a major component of the non-domestic grazing pressure, (b) commercial harvesting, the means of control that has the highest social acceptability, is ineffective due to the loss of markets and the actions of activist groups, (c) the task is largely beyond the capacity of individual landholders and (d) the same constraints do not apply to other non-domestic species (Hacker *et al.* 2019*b*). However, because of their unique status as protected wildlife, whose control by either commercial or non-commercial harvesting is regulated by State and Commonwealth governments, management of kangaroos is largely beyond the control (and, as noted above, capacity) of landholders. It currently represents a case of market failure because landholders acting in their own interest cannot be confidently expected to deliver outcomes consistent with public expectations (Hacker *et al.* 2019*b*).

Many pastoralists cite the tendency of kangaroos to graze preferentially in destocked paddocks (e.g. Wilson 1991*b*; Norbury and Norbury 1993) as a reason for maintaining continuous grazing practices, and their incursion into destocked paddocks can indeed limit the success of rangeland regeneration programs (Norbury *et al.* 1993). Some suggested approaches to this problem include establishing facilities such as self-mustering yards at water points to ensure that stock water supplies can be turned off when paddocks are destocked, resting areas as large as possible in an attempt to dilute the effect of any concentration, given the observation by Norbury and Norbury (1993) that kangaroo incursions into destocked paddocks are apparently from local rather than remote populations, and leaving a few sheep in a paddock to deter the influx of kangaroos (Hacker and McLeod 2003). However, neither the 'dilution' effect nor the effect of a low sheep stocking rate has been tested experimentally. Watson *et al.* (1988) demonstrated that kangaroo grazing was concentrated in the most lightly stocked paddocks in their grazing trial, particularly under poor seasonal conditions, suggesting that the latter option may not be realistic, but their study did not include comparison with an unstocked area. Closure of watering points in destocked paddocks should be practiced routinely and, although it may not necessarily lead to a reduction in kangaroo grazing pressure from the resident population, it may help deter increases due to incursion (Freudenberger and Hacker 1997). Temporary exclusion of kangaroos from sheep watering points by means of a low-lying electrified wire (the Finlayson trough, Norbury 1992) has potential to promote short-term concentration of kangaroos around the water, which may facilitate local harvesting or culling as an aid to paddock resting (Hacker and Freudenberger 1997).

Management of other non-domestic species presents fewer issues for landholders, provided the control methods are humane (Sinclair *et al.* 2019*a*, 2019*b*; Guideline 1.7). Some have been subject to ongoing or periodic control programs that are in part publicly funded (e.g. rabbits; camels, Hart and Edwards 2016); trapping/mustering and sale of unmanaged goats is both socially acceptable and can represent a significant source of income for landholders in some parts of the region (Khairo *et al.* 2011; Guideline 1.7).

Since management of TGP is such a fundamental issue for pastoralists in the southern rangelands, it is important that the equivalence of the various species on a relevant scale be understood. Estimates of the DSE ratings of most species (in various physiological states) are readily available, and are not repeated here, and although these are usually based on maintenance energy requirements, there is generally a reasonable correspondence between ratings on this scale and forage intake, and therefore contribution to TGP. However, for kangaroos, there has been considerable controversy about the appropriate rating. Pahl (2019*b*) showed that a rating of 1 DSE for a 50 kg kangaroo is more appropriate for assessing their contribution to total forage consumption than is the rating of 0.5, on the basis of basal metabolic rate or energy expended in grazing, widely accepted in recent years (Guideline 1.1).

Infrastructure development

Waters *et al.* (2019, appendix 2) described both 'exclusion fencing' and 'TGP fencing'. The former is aimed primarily at the exclusion of wild dogs, although with simultaneous impact on kangaroos, and is predominantly used to surround large areas or several properties in a 'cluster'; the latter is aimed at partial exclusion of unmanaged goats, kangaroos and wild dogs and is used for boundary or internal fences on individual properties. Interest in the establishment of both types of fence, and other fence designs aimed at deterring goats and kangaroos, has increased considerably in recent years and is indicative of the serious impact that wild dogs and non-domestic herbivores are perceived to have on pastoral enterprises, particularly sheep operations. Interest in these developments has also been stimulated by the availability of incentive funding from State and Commonwealth governments and, for cluster fences, establishment of formal agreements to ensure fence maintenance. Waters *et al.* (2019) cited increases in gross margin of up to 345% attributable to cluster fencing, but acknowledged that there is uncertainty about the biophysical and economic impacts of these investments. Given the range of fencing designs available, and establishment costs of up to A\$15 000 km^{-1}, it is important that careful consideration be given to the likely cost-effectiveness of new investment (Principle 2; Guideline 2.1).

Where new internal fences are established, the advice generally given by extension agencies is to fence to land type as much as possible (Guideline 2.2). Given the scale of pastoral operations in the southern rangelands, this concept would probably not entirely deprive animals of the benefits of functional heterogeneity noted above, and is supported by the common observation that small areas of preferred land types fenced with large areas of less preferred types are often severely degraded.

The size of paddocks is the subject of considerable debate but there is little objective guidance that is specific to the region. In the chenopod shrublands of South Australia, one model of development based on subdivision into paddocks of ~2000 ha, each with a permanent watering point and grazed (continuously) by flocks of 250–350 sheep, has provided profitable pastoralism and well preserved shrublands (Lange *et al.* 1984), although even here some long-term loss of shrubs has occurred (Andrew and Lange 1986). Smaller paddocks could be expected to provide more uniform utilisation of the landscape, and this mechanism probably accounts for much of the increase in carrying capacity claimed for holistic management, with its intensive subdivision, in commercial situations (Norton 2003). Some pastoralists would advocate that paddocks should simply be small enough to allow mustering and stock handling to be completed in one day.

A major trend in recent decades has been the development of self-mustering facilities, or trap yards, at watering points, initially in Western Australia, but subsequently throughout the eastern states (see e.g. Connelly *et al.* 2000). These facilities offer not only a cost-effective means of mustering livestock where surface water is unavailable, but also a means of trapping unmanaged goats and restricting access to water by kangaroos when paddocks are destocked (Guideline 2.3). Although closure of the traps should ideally exclude kangaroos from water entirely, individuals do sometimes gain entry and present an animal welfare issue if they cannot exit; this issue needs to be addressed, either by trap design or management. As with fencing, the implementation of trap yards has been substantially assisted in recent years by the availability of incentive funding from regional natural resource management organisations.

Throughout much of the grazed southern rangelands, there is little need for the development of additional livestock watering points, apart from what may be required to allow subdivision for more intensive grazing systems. The proliferation of artificial waters in the region has been noted above so that few areas are beyond the grazing range of livestock and grazing distribution is not seriously restricted by limited water supplies (Fensham and Fairfax 2008), even in those areas where saline water limits the grazing range of animals. The situation is such that a reduction in the number of watering points, creating water-remote areas, could be desirable from the perspective of biodiversity conservation (Guideline 4.1).

Self-herding, whereby attractants and positive reinforcement are used to encourage animals to move around landscapes without the need for extensive subdivisional fencing, has recently been employed by some pastoralists in the southern rangelands to manage livestock distribution and provide rest to areas as needed (Revell *et al.* 2015). Unfortunately, the hoped-for developments in virtual fencing (Anderson 2007) have not materialised to date on a commercial scale.

Invasive native scrub

As noted above, thickening of native woody vegetation, formerly called 'woody weeds' and currently 'INS', has been a feature of the eastern part of the southern rangelands, particularly the Mulgalands of south-western Queensland and north-western New South Wales, and the Cobar Peneplain in western New South Wales. Elsewhere in the region, changes in the composition and density of mid-storey shrub species have been observed under pastoral use (e.g. Watson and Novelly 2012, in the arid zone of Western Australia), or degraded rangelands have been invaded by woody exotic species (e.g. *Acacia nilotica* in the north-east of the region). However, our interest here is in the impact of INS in the higher-rainfall environments in the east of the region where the issue was reported as early as the 1870s (Noble undated, p. 8) and has continued to be of major concern to landholders. The nature and management of this problem have been the subjects of extensive research from the 1960s to the 1990s by CSIRO and state agencies in New South Wales and Queensland (Noble undated, pp. 6–7). The major outcomes, and guides to practical management, are summarised in Noble (undated), CWCMA and WCMA (2010) and WLLS (2019).

The extensive experience of both researchers and landholders has shown that there is no one-off solution to encroachment of INS (Principle 3). An overall approach will necessarily involve control of TGP, grazing management that maintains competitive perennial grasses under varying seasonal conditions, and treatment of regrowth. Monitoring the presence of INS seedlings when seasonal conditions are conducive to establishment will be an essential feature of this process (Guideline 3.1). Planning to address all of these components should be part of both short- and medium–long-term property management planning (Principle 3). Because open areas provide the highest economic return, and the cost of maintaining them is much lower than the cost of restoring encroached areas, such maintenance should always be the first priority of INS management (Guideline 3.2). This priority is emphasised by the fact that only small increases in shrub cover are sufficient to reduce forage production, which declines rapidly as shrub cover increases (Guideline 3.2). Remaining areas should be prioritised for treatment based on the expected costs and benefits, and the ease of incorporating INS management into overall property management (Guideline 3.3).

Management of INS at property scale will involve production of an appropriate property plan on which the areas designated for treatment can be identified and prioritised, determining whether a paddock should be retained for grazing or used to obtain income via carbon credits (Guideline 3.4), and development of an appropriate post-treatment strategy (e.g. in relation to TGP and grazing management) to ensure that the anticipated benefits of any investment can be realised. Because it is difficult to provide accurate information regarding the cost of an INS control program in a specific situation, a simple net present value approach has been proposed (WLLS 2019) to estimate the economic benefit of a successful treatment program and, thus, an estimate of the maximum amount that could be reasonably invested (Guideline 3.3).

It is notable that although management burning is by far the cheapest control option available (WLLS 2019), and is effective against seedlings of all invasive species, even though some are tolerant of fire as adults (Hodgkinson and Harington 1985), it has not been widely adopted. Reasons include the reluctance of graziers to use the high levels of biomass produced only on decadal time scales for fuel rather than forage, the risk of erosion of bare soil surfaces, concerns (largely unfounded) that fire may stimulate the germination of more shrubs or 'bake' the soil, fears of losing control of a fire, and the limited manpower now available in many areas to undertake a well planned burn. The extent to which Indigenous traditional knowledge could be incorporated into the use of fire for INS management (see Nielsen *et al.* 2020) seems not to have been substantially explored. Notably though, Purvis (1986) provided an example from central Australia of the effective use of small-scale, opportunistic burning over the long-term for INS management, effectively restoring Aboriginal practices.

While shrub encroachment is generally viewed as negatively affecting pastoral production, there is also a growing body of evidence that some ecosystem services are not necessarily affected, and may be enhanced, by encroachment so that no single state (including grassland without shrubs) will maximise all services (Eldridge and Soliveres 2014). These authors emphasised that the effects of shrubs on ecosystems are strongly scale-, species- and environment-dependent. They considered that overgrazing is the primary determinant of ecosystem degradation rather than encroachment *per se*, although from a pastoral perspective, we would argue that encroachment can be both a symptom of land degradation (when it results in part from the reduction of perennial grass competition) and a cause (when seasonal conditions permit the encroachment of shrubs into otherwise healthy grassland). However, we would not dispute their view that in some situations at least, money would be better invested in projects to maximise carbon sequestration, enhance biodiversity, or improve soil fertility and conservation rather than in shrub removal.

Biodiversity conservation in pastoral landscapes

There is a growing awareness among pastoralists and industry organisations of the requirement for demonstrable environmental stewardship and animal welfare to underpin the social licence and sustainability of the pastoral industry (Waters *et al.* 2019), and that landholders' duty of care extends beyond the maintenance of pastoral values (Principle 4). Similarly, as the need for global food security increases, livestock grazing management that promotes biodiversity values may offer an alternative approach for broad-scale conservation while achieving dual production and ecological outcomes (Dorrough *et al.* 2004). In global terms, much of Australia's rangeland, both grazed and ungrazed, offers a chance to maintain a vast functioning environment that has been forfeited in many overseas rangeland areas (Woinarski and Fisher 2003).

Silcock and Fensham (2019), in their extensive review of the impacts of 160 years of pastoralism, concluded that conservation of plant biodiversity seems largely compatible with commercial pastoralism, at least in inland eastern Australia. This is consistent with other studies that have suggested that careful grazing management can achieve dual conservation and production outcomes and play a role in increasing biodiversity in agricultural landscapes (Curry and Hacker 1990; Dorrough *et al.* 2004; Fensham *et al.* 2011, 2014; Savory 2013; Silcock and Fensham 2013; McDonald *et al.* 2019*b*).

Domestic livestock (sheep, cattle) are sometimes considered to have a greater impact on biodiversity than other native and introduced species. Tiver and Andrew (1997), for example, concluded that, at existing levels of herbivory, sheep were the most important vertebrate herbivore affecting regeneration of 18 tree and shrub species in South Australia, and that the impacts of non-domestic vertebrates (rabbits, goats and kangaroos) were much less important. Similarly, Eldridge *et al.* (2018) reported little effect of kangaroo grazing on biodiversity, even at high densities (Guideline 1.4). However, 'competition and land degradation by unmanaged goats' is listed as a key threatening process under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999*. Goats compete with native fauna, such as the yellow-footed rock wallaby, for food, water and shelter, and contribute to other degradation processes (Department of Sustainability, Environment, Water, Population and Communities 2011), so that goat population management should be undertaken, particularly within sensitive areas (Guideline 4.2).

Where specific habitats that are important for biodiversity occur on pastoral leases, landholders arguably have a greater duty of care to exercise stewardship of them (Guideline 4.2). This might apply, for example, to mound springs, yellow footed rock wallaby habitat, or other specific areas that Morton *et al.* (1995) considered should be established as 'excised management units' to protect non-pastoral values. Such stewardship need not impose substantial additional costs on landholders. Removal of unmanaged goats, for example, can be an important source of income (Khairo *et al.* 2011, 2013).

Given the 'catastrophic' record of mammal extinctions in the arid and semiarid zones attributable primarily to introduced cats and foxes, as noted above, attempts to control this impact should be beneficial for biodiversity conservation in pastoral landscapes. Control of foxes, in particular, can also be expected to provide an economic benefit in areas where predation on domestic flocks (particularly lambing ewes) is significant (Jones *et al.* (2006); Guideline 4.3). There has been considerable interest in recent years in the potential to control these exotic predators and facilitate biodiversity conservation by positive management of dingoes as a top predator. Moseby *et al.* (2012) provided evidence that dingoes can suppress both cats and foxes, particularly the latter, within a securely fenced 'dingo paddock,' consistent with much anecdotal evidence. However, reviews of the potential for positive management of dingoes to promote biodiversity conservation warn strongly that evidence to support this approach is inconclusive, and that adverse consequences, both ecological and economic, could result (Allen *et al.* 2012, 2013; Fleming *et al.* 2012).

Reviews of the impact of alternative grazing systems on biodiversity provide no clear evidence for the advantage of one system over another (e.g. Dorrough *et al.* 2004; McDonald *et al.* 2019*a*; Waters *et al.* 2019). Rotational grazing systems are believed to favour biodiversity because they reduce selective grazing and allow for recovery of palatable species between grazing events (Norton 1998; Teague *et al.* 2008). However, few studies examining biodiversity under contrasting grazing systems have been undertaken in the southern rangelands. In western New South Wales, biodiversity under rotational grazing systems has been reported to be comparable to ungrazed areas, and at times greater than in continuously grazed areas (Waters *et al.* 2017; McDonald *et al.* 2019*a*, 2020).

We have argued above that grazing should be managed in a tactical grazing framework, which recognises that seasonal and/ or economic conditions may not always permit grazing to be managed according to the strategy originally defined to achieve the objective for a particular management unit. When compromises are required, the implications for biodiversity outcomes, as well as short- and long-term production outcomes, should be considered (Guideline 4.4).

The impact of grazing on biodiversity will vary depending on location, herbivore type, grazing intensity and grazing system. While some authors have considered the impact of grazing on biodiversity in the southern rangelands to be generally negative (Eldridge *et al.* 2016; Eldridge and Delgado-Baquerizo 2017), we would argue on the basis of the above discussion that well managed grazing can be compatible with conservation of biodiversity in the region. Further, since markets for carbon sequestration, biodiversity conservation and other ecosystem services are now either established or are emerging, landholders should have the opportunity to obtain financial reward from management that delivers public goods beyond what is reasonably required by their duty of care (Guideline 4.5).

Prospects for sustainable land use

A future for pastoralism?

Questions about the viability of pastoralism in the southern rangelands have long been raised, reflected in efforts to classify bioregions, in terms of their suitability for pastoralism, using axes of 'likely pastoral benefit' and 'likely risk to public values' (Stafford-Smith *et al.* 2000), to assess the quality of pastoral management (Pickup and Stafford-Smith 1993), and to encourage administrative provisions to assure conservation of non-pastoral values (Morton *et al.* 1995). We have also noted the operation of several publicly funded programs intended to achieve a re-vitalisation of the pastoral industry in the region, and their limited success. Several other substantial projects have undertaken a consultative approach to defining a desirable future for various parts of the region, but without any marked, lasting influence (e.g. DAWA 2002; Project 21C in New South Wales).

We accept that there are parts of the southern rangelands the future of which does not lie in the continuation of pastoralism, either in the traditional form or with the implementation of more progressive approaches to grazing and natural resource management. However, we are not able, in this paper, to provide a detailed account of the likely distribution of these areas beyond the generalisation that they are most likely to occur at the lower end of the productivity spectrum identified previously, such as in the arid zone of Western Australia where many leases are considered non-viable, or in areas with a high conservation value (van Etten 2013). We anticipate that the emergence of alternative land uses, as discussed previously, will be an important factor in providing a market-based solution to the allocation of land resources within the region, although how this may function could vary among jurisdictions. However, we also acknowledge that the market alone may not be sufficient to ensure that land use is appropriately matched with land condition/capability. A role for government will remain, particularly at State and Territory levels, in ensuring that policy settings and financial assistance facilitate a rational, market-based allocation of land to the most appropriate use and, where market failure is evident, that last resort measures are available to remove land from the pastoral domain.

Prospects for sustainable pastoral land use

We would argue that, at one level, the pastoral industry overall in the southern rangelands has never been better placed to achieve sustainability than at the present time. This situation arises in part from the public investment made over the past two decades in a range of regional programs aimed at revitalising and restructuring the industry. Although these have, by no means, achieved all of their stated objectives, they have improved the potential for sustainable management by, for example, supporting investment in infrastructure that allows better control of both domestic and non-domestic herbivores, and assisting the development of some emerging industries such as on-farm tourism and rangeland goats (Table 1; e.g. URS 2015). Current technological developments also support economically efficient pastoral production in ways not previously available (e.g. drones for remote monitoring of livestock and infrastructure, 'walk-over' weighing, farm and grazing management software packages, Internet-based services for both market and seasonal data and forecasts), even if further developments are desirable to tailor the application of available technology to specific property situations. Furthermore, there is a growing awareness, as noted above, of the need for demonstrable environmental stewardship. We, therefore, consider that pastoralism conducted in accordance with the principles and guidelines outlined above has good prospects for ecological, economic and social sustainability in those areas where it continues. Nevertheless, the application of these principles/guidelines may still be constrained by many factors beyond the control of individual landholders, some of which are listed below.

Inadequate policies for management of kangaroos and other non-domestic herbivores

The management of kangaroos is a key component of ecologically sustainable management in the region because they represent a significant component of TGP, their control by commercial harvesting has been adversely affected in recent years by loss of markets and stakeholder activism, and their control is largely beyond the capacity of individual landholders (Hacker *et al.* 2019*b*). These characteristics distinguish them from other non-domestic herbivores which landholders can more readily control. We consider that the market failure represented by the present kangaroo management arrangements, whereby neither the kangaroo industry nor landholders, acting in their own interests, can deliver outcomes for natural resource management and animal welfare that are socially acceptable, urgently requires a paradigm shift in kangaroo management. We are unable to argue in detail here the possible nature of this shift but note that several suggestions have been made in recent times, including the adoption of an active adaptive management approach by wildlife management authorities (McLeod and Hacker 2019) and the granting to landholders of a form of proprietorship or custodianship over kangaroos (Wilson and Edwards 2019; Wilson *et al.* 2020). While other non-domestic herbivores (e.g. camels, pigs and goats) represent a lesser, or more localised, challenge for management of TGP, we concur with Nielsen *et al.* (2020) that their management would be assisted by the establishment or further development of market-based approaches, and development of appropriate product branding.

Impact of climate change

The likely impacts of climate change on the region have been outlined above. Marshall (2015) considered that only 16% of beef producers in northern Australia had sufficient adaptive capacity to cope with climate change. We would expect that a similar situation would apply to the southern rangelands. Although a considerable range of financial instruments (e.g. Farm Management Deposits) and technical information is available to assist producers manage climatic extremes, the particular situation of the individual business, and the particular sequence of climatic events, may easily override the best attempts to manage according to the principles and guidelines given above. Climate change can thus be expected to increase the difficulty of achieving sustainable land use across the region. It also highlights the desirability of integrating rangeland enterprises with operations in less variable environments to improve the overall resilience of businesses.

Failure of policy to operate at appropriate spatial and temporal scales

Since trends in land condition are variable in time and space, feedback from monitoring programs to policy makers will need to be highly granular to be effective. Policies that seek to influence land condition will need to be guided by monitoring feedback at a scale relevant to regional management, and not by broad generalisations or perceptions. Nielsen *et al.* (2020, p. 364) noted a similar need for spatial and temporal flexibility in policy application, particularly in relation to drought. Failure of policy settings to recognise the particular requirements of local contexts could be regarded as a form of sovereign risk for individual landholders. It would represent a failure to implement the adaptive model of natural resource governance that Marshall and Stafford-Smith (2010) considered most appropriate for remote areas with highly variable environments, such as the southern rangelands, and may impede the mobilisation of local enthusiasms and skills in pursuit of sustainable pastoral land use across the region.

Limited resources for research, development and extension (R, D and E)

Resources available for R, D and E in the region have always been low and have declined substantially over recent decades (Hacker 2013), consistent with the declining importance of the southern rangelands in the overall pastoral economy, relative to the more productive northern savannas (Foran *et al.* 2019). It is unlikely that this situation will be reversed unless some of the initiatives proposed by Nielsen *et al.* (2020) come to fruition, such as establishment of an Outback Commission and/or an Outback Capital Trust Fund to divert a portion of royalties from mining in the rangelands to R, D and E. Although information gaps can be readily identified (e.g. effects of different grazing strategies/management practices on biodiversity, Dorrough *et al.* 2004; management requirements of grazing sensitive species, Silcock and Fensham 2019; effect of animal impact on the functioning of arid and semiarid ecosystems, Hacker 1993), the capacity to address these through critical research will be strictly limited. Less conventional forms of R, D and E will be required, based around approaches such as adaptive management, action learning and exploitation of natural experiments which involve stakeholders, including Indigenous people, in the design, implementation, interpretation and adoption of the outcomes. Establishment of 'innovation hubs' *sensu* Nielsen *et al.* (2020) would also be beneficial.

Prospects for sustainability under alternative land uses

Carbon farming has considerable potential to contribute to increased socio-ecological resilience in the southern rangelands, because, in addition to the primary objective of carbon sequestration, it can also deliver co-benefits such as diversification of land uses and income streams, a range of consequential community benefits, and ecological benefits including increased biodiversity and habitat provision, improvements to soil health, structure and water holding capacity, management of erosion and salinity, and water quality (Baumber *et al.* 2020). However, these authors also noted the potential for negative impacts arising from policy uncertainty, loss of future land use flexibility, possible social divisions arising from carbon farming eligibility criteria, and landholder absenteeism. Additionally, ecological risks may be associated with possible exacerbation of INS encroachment, and simplification of diverse ecosystems. Given that the legislated focus of the Emissions Reduction Fund (ERF) is least-cost carbon abatement, it could produce perverse outcomes unless complementary incentive schemes are introduced to value co-benefits (e.g. the Queensland Government's co-benefits standards for assessing carbon farming projects under its Land Restoration Fund), or eligibility rules for ERF projects are modified (Baumber *et al.* 2020).

We are not aware of any potential for perverse outcomes that would attend the use of land for provision of ecosystem services or renewable energy generation.

Conclusions

Hunt *et al.* (2014) expressed the requirements for grazing management of Australia's northern rangelands in terms of four principles and 13 guidelines, compared with four principles and 19 guidelines discussed above and listed in Table 3. However, their principles and guidelines related specifically to the four topics of stocking rate, pasture resting, prescribed fire and paddock size/water distribution. The first three of these topics are subsumed, in our summation, under the philosophy of tactical grazing (Principle 1), whereas we place more explicit emphasis on development of infrastructure for management of TGP (Principle 2) and conservation of biodiversity within pastoral production systems (Principle 4). Although there is considerable overlap between the two summations, particularly at the guideline level, these differences reflect both the broad ecological contrasts between the two regions (e.g. the abundance of kangaroos and other non-domestic grazers in the southern rangelands, and the limited pastoral potential of much of this region), together with our explicit attempt to recognise the increasing societal preference for non-pastoral values.

Stakeholders in Australia's rangelands aspire to 'resilient and sustainable rangelands that provide cultural, societal, environmental and economic outcomes simultaneously' (Nielsen *et al.* 2020). We have attempted to elucidate the more specific requirements of this vision in relation to the southern rangelands.

We acknowledge that achievement of this vision will almost certainly involve some continued withdrawal of land from pastoral use. Where pastoralism continues, we consider that sustainable land use can be achieved by application of four management principles and 19 associated management guidelines. These management principles are (1) manage grazing in a tactical risk management framework, (2) develop infrastructure to allow best management of both domestic and non-domestic grazing pressure, (3) incorporate INS management, where required, into overall property management on an ongoing basis and (4) manage grazing to enhance biodiversity conservation at landscape scale.

Due to the partial success of several publicly funded regional reconstruction programs, the pastoral industry is today probably better equipped than previously to implement these principles and guidelines. However, sustainable land use under pastoralism will still be subject to constraints not under the control of individual landholders and will require the development of appropriate policy settings, particularly in relation to kangaroo management, climate change, and governance arrangements, as well as innovative approaches to R, D and E.

The future pastoral industry will co-exist with the new industry of carbon sequestration. This will infuse large amounts of capital into those areas that are able to satisfy the requirements of the protocols, providing a range of socio-ecological benefits but with the potential for perverse outcomes unless policy initiatives appropriately value the co-benefits which the industry can provide. Industries that utilise the major renewable energy resources of the region, or are based on provision of ecosystem services, would seem to have considerable potential. They are considered unlikely to have adverse ecological consequences, although the former may be limited by the remoteness of much of the area.

Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

Data used in the paper are not available in a public repository but may be obtained from the corresponding author.

Funding

This research did not receive any specific funding.

Acknowledgements

This paper owes much to both formal and informal input from Alec Holm whose contribution is gratefully acknowledged. Peter Worsley and Warren Smith (both of NSW Department of Primary Industry) provided the data for vegetation and soil characteristics, and land use, respectively, based on the boundary of the southern rangelands (Fig. 1) originally developed by Simon McDonald (Charles Sturt University). Don Burnside, Paul Novelly, Trudie Atkinson, Yohannes Alemseged, Ian Watson and two anonymous reviewers provided very helpful comments which substantially improved the quality of the manuscript, and also brought several relevant references to our attention. Financial support for RBH was provided by the Australian Rangeland Society and is much appreciated.

References

ABARES (2016). Land use of Australia 2010–11. Department of Agriculture, Water and the Environment, Australian Government. Available at: https://www.agriculture.gov.au/abares/aclump/land-use/land-use-of-australia-2010-11 [accessed 3 November 2020].

Alemseged, Y., and Hacker, R. B. (2014). Introduction of Dorper sheep into Australian rangelands: implications for production and natural resource management. *The Rangeland Journal* **36**, 85–90. doi:10.1071/RJ13034

Alemseged, Y., Hacker, R. B., Smith, W. J., and Melville, G. J. (2011). Temporary cropping in semi-arid shrublands increases native perennial grasses. *The Rangeland Journal* **33**, 67–78. doi:10.1071/RJ10022

Allen, B. L., Fleming, P. J. S., Hayward, M., and Allen, L. R. (2012). Top-predators as biodiversity regulators: contemporary issues affecting knowledge and management of dingoes in Australia. *In*: 'Biodiversity Enrichment in a Diverse World'. Chapter 4. (Ed. Gbolagade Akeem Lameed.) pp. 85–132. (InTech: Rijeka, Croatia.) doi:10.5772/50246

Allen, B. L., Fleming, P. J. S., Allen, L. R., Engeman, R. M., Ballard, G., and Leung, L. K.-P. (2013). As clear as mud: A critical review of evidence for the ecological roles of Australian dingoes. *Biological Conservation* **159**, 158–174. doi:10.1016/j.biocon.2012.12.004

Anderson, D. M. (2007). Virtual fencing: past, present and future. *The Rangeland Journal* **29**, 65–78. doi:10.1071/RJ06036

Andrew, M. H., and Lange, R. T. (1986). Development of a new piosphere in arid chenopod shrubland grazed by sheep. 2. Changes to the vegetation. *Australian Journal of Ecology* **11**, 411–424. doi:10.1111/j.1442-9993.1986.tb01410.x

Ansell, D., Freudenberger, D., Munro, N., and Gibbons, P. (2016). The cost-effectiveness of agri-environment schemes for biodiversity conservation: a quantitative review. *Agriculture, Ecosystems & Environment* **225**, 184–191. doi:10.1016/j.agee.2016.04.008

Archer, S., Schimel, D. S., and Holland, E. A. (1995). Mechanisms of shrubland expansion: land use, climate or CO_2? *Climatic Change* **29**, 91–99. doi:10.1007/BF01091640

Ash, A. J., and Stafford-Smith, D. M. (1996). Evaluating stocking rate impacts in rangelands: animals don't practice what we preach. *The Rangeland Journal* **18**, 216–243. doi:10.1071/RJ9960216

Atkinson, T., Hacker, R. B., Melville, G. J., and Reseigh, J. (2019). Land managers' and service providers' perspectives on the magnitude, impact and management of non-domestic grazing pressure in the southern rangelands of Australia. *The Rangeland Journal* **41**, 461–476. doi:10.1071/RJ19065

Australian Wildlife Conservancy (2021). Available at: https://www.australianwildlife.org/ [accessed 10 May 2021].

Barnes, M. K., Norton, B. E., Maeno, M., and Malechek, J. C. (2008). Paddock size and stocking density affect spatial heterogeneity of grazing. *Rangeland Ecology and Management* **61**, 380–388. doi:10.2111/06-155.1

Bastin, G. and the ACRIS Management Committee (2008). 'Rangelands — Taking the Pulse.' Published on behalf of the ACRIS Management Committee by the National Land & Water Resources Audit, Canberra, ACT, Australia.

Baumber, A., Waters, C., Cross, R., Metternicht, G., and Simpson, M. (2020). Carbon farming for resilient rangelands: people, paddocks and policy. *The Rangeland Journal* **42**, 293–307. doi:10.1071/RJ20034

Bean, J. M., Melville, G. J., Hacker, R. B., and Clipperton, S. P. (2015). Seed availability, landscape suitability and the regeneration of perennial grasses in moderately degraded rangelands in semiarid Australia. *The Rangeland Journal* **37**, 249–259. doi:10.1071/RJ14105

Beeton, R. J. S., Page, M. J., Slaughter, G., and Greenfield, R. (2005). 'Study of Fodder Harvesting in Mulga Regional Ecosystems.' (University of Queensland.)

Boulaire, F. (2021). Export possibilities mean Australia's clean-energy future can also be the world's. *In*: 'North of 26° South and the Security of Australia'. pp. 62–63. (Australian Strategic Policy Institute.) Available at: https://www.aspistrategist.org.au/export-possibilities-mean-australias-cleanenergy-future-can-also-be-the-worlds [accessed 26 September 2021]

Bowman, A., Alemseged, Y., Melville, G., Smith, W., and Syrch, F. (2009). Increasing the perennial grass component of native pastures through grazing management in the 400–600 mm rainfall zone of central western NSW. *The Rangeland Journal* **31**, 369–376. doi:10.1071/RJ08032

Briske, D. D., Derne, J. D., Brown, J. R., Fuhlendorf, S. D., Teague, W. R., Havstad, K. M., Gillen, R. L., Ash, A. J., and Willms, W. D. (2008). Rotational grazing on rangelands: reconciliation of perception and experimental evidence. *Rangeland Ecology and Management* **61**, 3–17. doi:10.2111/06-159R.1

Briske, D. D., Sayre, N. F., Huntsinger, L., Fernandez-Gimenez, M., Budd, B., and Derner, J. D. (2011). Origin, persistence, and resolution of the rotational grazing debate: integrating human dimensions into rangeland research. *Rangeland Ecology and Management* **64**, 325–334. doi:10.2111/REM-D-10-00084.1

Briske, D. D., Coppock, D. L., Illius, A. W., and Fuhlendorf, S. D. (2020). Strategies for global rangeland stewardship: assessment through the lens of the equilibrium–non-equilibrium debate. *Journal of Applied Ecology* **57**, 1056–1067. doi:10.1111/1365-2664.13610

Bush Heritage Australia (2021). Available at: https://www.bushheritage.org.au/ [accessed 10 May 2021].

Buxton, R., and Stafford-Smith, M. (1996). Managing drought in Australia's rangelands: four weddings and a funeral. *The Rangeland Journal* **18**, 292–308. doi:10.1071/RJ9960292

Cairns, K. M., Crowther, M. S., Nesbitt, B., and Letnic, M. (2021). The myth of wild dogs in Australia: are there any out there? *Australian Mammalogy*. doi:10.1071/AM20055

Campbell, T., and Hacker, R. (2000). 'The glove box guide to tactical grazing management for the semi-arid woodlands.' (NSW Agriculture: Dubbo, NSW, Australia.)

Cockfield, G., Shrestha, U. B., Waters, C., and Garland, F. (2017). Assessing the economic impacts of carbon farming in western NSW. *In*: 'Proceedings of the 19th Australian Rangeland Society Biennial Conference'. (Australian Rangeland Society: Australia.)

Condon, R. W. (1968). Estimation of Grazing Capacity on Arid Grazing Land. *In*: 'Land Evaluation, Papers of a CSIRO Symposium in Cooperation with UNESCO', 26–31 August 1968. (Ed. G. A. Stewart.) pp. 112–124. (McMillan Australia.)

Condon, R. W., Newman, J. C., and Cunningham, G. M. (1969). Soil erosion and pasture degeneration in central Australia Part III. The assessment of grazing capacity. *Journal of the Soil Conservation Service of N.S.W.* **25**, 225–250.

Connelly, P., Horrocks, D., Pahl, L., and Warman, K. (2000). Cost effective and multipurpose self-mustering enclosures for stock. Department of Primary Industries Information Series Q100077. Department of Primary Industries, Brisbane.

Cooke, J., Groves, R. H., and Ash, J. (2011). The distribution of *Carrichtera annua* in Australia: introduction, spread and probable limits. *The Rangeland Journal* **33**, 23–35. doi:10.1071/RJ10001

CSIRO and Bureau of Meteorology (2021). Climate change in Australia. Available at: https://www.climatechangeinaustralia.gov.au/en/projections-tools/regional-climate-change-explorer/clusters/?current=RA&tooltip=true&popup=true [accessed 24 September 2021].

Cunningham, R., Silcocks, A., O'Connor, J., and Weston, M. (2007). A statistical analysis of temporal trends in detection rates of birds in the rangelands, using Atlas of Australian Birds data, 1999–2006. Report to Department of the Environment and Water Resources, Canberra, by Birds Australia, Melbourne, Vic., Australia.

Curry, P., and Hacker, R. (1990). Can pastoral grazing management satisfy endorsed conservation objectives in arid Western Australia? *Journal of Environmental Management* **30**, 295–320. doi:10.1016/0301-4797(90)90025-R

CWCMA and WCMA (Central West Catchment Management Authority and Western Catchment Management Authority) (2010). 'Managing invasive native scrub to rehabilitate native pastures and open woodlands. A Best Management Practice Guide for the Central West and Western Catchments.' (Central West Catchment Management Authority: Wellington, NSW, Australia; *and* Western Catchment Management Authority: Cobar, NSW, Australia.)

DAWA (2002). 'Rangeways: Community-based Planning for Ecologically Sustainable Land Use in the Western Australian Goldfields.' Miscellaneous Publication 9/2002. (Department of Agriculture, Western Australia: Perth, WA, Australia.)

Denham, A. J., and Auld, T. D. (2004). Survival and recruitment of seedlings and suckers of trees and shrubs of the Australian arid zone following habitat management and the outbreak of rabbit calicivirus disease (RCD). *Austral Ecology* **29**, 585–599. doi:10.1111/j.1442-9993.2004.01393.x

Department of Primary Industries and Regional Development (2019). Status of the Western Australian pastoral rangelands 2019: condition, trend and risk. Department of Primary Industries and Regional Development, Perth, WA, Australia. Available at: https://www.agric.wa.gov.au/sites/gateway/files/Status%20of%20the%20Western%20Australian%20pastoral%20rangelands%202019%3A%20condition%2C%20trend%20-and%20risk%20%28PDF%204.5MB%29.pdf [accessed 10 December 2020].

Department of Sustainability, Environment, Water, Population and Communities (2011). The feral goat (*Capra hircus*). Invasive species fact sheet. BIO56.0610. Department of Sustainability, Environment, Water, Population and Communities, Australian Government. Available at: http://www.environment.gov.au/system/files/resources/0b78ac9f-c442-4fe1-9f96-8205f505a4c8/files/feral-goat.pdf [accessed 18 January 2021].

di Virgilio, A., Lambertucci, S. A., and Morales, J. M. (2019). Sustainable grazing management in rangelands: over a century searching for a silver bullet. *Agriculture, Ecosystems & Environment* **283**, 106561. doi:10.1016/j.agee.2019.05.020

Díaz, S., Lavorel, S., McIntyre, S. U. E., Falczuk, V., Casanoves, F., Milchunas, D. G., Skarpe, C., Rusch, G., Sternberg, M., Noy-Meir, I., Landsberg, J., Zhang, W. E. I., Clark, H., and Campbell, B. D. (2007). Plant trait responses to grazing: a global synthesis. *Global Change Biology* **13**, 313–341. doi:10.1111/j.1365-2486.2006.01288.x

Donohue, R. J., Roderick, M. L., McVicar, T. R., and Farquhar, G. D. (2013). Impact of CO_2 fertilization on maximum foliage cover across the globe's warm, arid environments. *Geophysical Research Letters* **40**, 3031–3035. doi:10.1002/grl.50563

Dorrough, J., Yen, A., Turner, V., Clark, S., Crosthwaite, J., and Hirth, J. (2004). Livestock grazing management and biodiversity conservation in Australian temperate grassy landscapes. *Australian Journal of Agricultural Research* **55**, 279–295. doi:10.1071/AR03024

Eldridge, D. J., and Delgado-Baquerizo, M. (2017). Continental-scale impacts of livestock grazing on ecosystem supporting and regulating services. *Land Degradation & Development* **28**, 1473–1481. doi:10.1002/ldr.2668

Eldridge, D. J., and Soliveres, S. (2014). Are shrubs really a sign of declining ecosystem function? Disentangling the myths and truths of woody encroachment in Australia. *Australian Journal of Botany* **62**, 594–608. doi:10.1071/BT14137

Eldridge, D. J., Poore, A. G., Ruiz-Colmenero, M., Letnic, M., and Soliveres, S. (2016). Ecosystem structure, function and composition in rangelands are negatively affected by livestock grazing. *Ecological Applications* **26**, 1273–1283. doi:10.1890/15-1234

Eldridge, D. J., Delgado-Baquerizo, M., Travers, S. K., Val, J., Oliver, I., and Kardol, P. (2017). Do grazing intensity and herbivore type affect soil health? Insights from a semi-arid productivity gradient. *Journal of Applied Ecology* **54**, 976–985. doi:10.1111/1365-2664.12834

Eldridge, D. J., Delgado-Baquerizo, M., Travers, S. K., Val, J., Oliver, I., Dorrough, J. W., Soliveres, S., and Müller, J. (2018). Livestock activity increases exotic plant richness, but wildlife increases native richness, with stronger effects under low productivity. *Journal of Applied Ecology* **55**, 766–776. doi:10.1111/1365-2664.12995

ERF (Emissions Reduction Fund) (2020). Emissions Reduction Fund project map. Available at: http://www.cleanenergyregulator.gov.au/ERF/project-and-contracts-registers/interactive-map [accessed 25 June 2020].

Fargher, J. D., Howard, B. M., Burnside, D. G., and Andrew, M. H. (2003). The economy of the Australian rangelands: myth or mystery? *The Rangeland Journal* **25**, 140–156. doi:10.1071/RJ03012

Fensham, R. (1998). The grassy vegetation of the Darling Downs, south-eastern Queensland, Australia. Floristics and grazing effects. *Biological Conservation* **84**, 301–310. doi:10.1016/S0006-3207(97)00105-5

Fensham, R., and Fairfax, R. (2008). Water-remoteness for grazing relief in Australian arid-lands. *Biological Conservation* **141**, 1447–1460. doi:10.1016/j.biocon.2008.03.016

Fensham, R., Fairfax, R., and Dwyer, J. (2010). Vegetation responses to the first 20 years of cattle grazing in an Australian desert. *Ecology* **91**, 681–692. doi:10.1890/08-2356.1

Fensham, R., Silcock, J., and Dwyer, J. (2011). Plant species richness responses to grazing protection and degradation history in a low productivity landscape. *Journal of Vegetation Science* **22**, 997–1008. doi:10.1111/j.1654-1103.2011.01305.x

Fensham, R. J., Silcock, J. L., and Firn, J. (2014). Managed livestock grazing is compatible with the maintenance of plant diversity in semidesert grasslands. *Ecological Applications* **24**, 503–517. doi:10.1890/13-0492.1

Fisher, A., Hunt, L., James, C., Landsberg, J., Phelps, D., Smyth, A., and Watson, I. (2004). Review of total grazing pressure management issues and priorities for biodiversity conservation in rangelands: a resource to aid NRM planning. Desert Knowledge CRC Project Report No. 3. Desert Knowledge CRC and Tropical Savannas Management CRC, Alice Springs, NT, Australia.

Fisher, A., Hunt, L., James, C., Landsberg, J., Phelps, D., Smyth, A., and Watson, I. (2005). 'Management of total grazing pressure. Australian Government.' (Department of the Environment and Heritage, Desert Knowledge CRC and Tropical Savannas CRC: Alice Springs, NT, Australia.)

Fleming, P. J. S., Allen, B. L., and Ballard, G.-A. (2012). Seven considerations about dingoes as biodiversity engineers: the socioecological niches of dogs in Australia. *Australian Mammalogy* **34**, 119–131. doi:10.1071/AM11012

Foran, B., Stafford-Smith, M., Burnside, D., Andrew, M., Blesing, D., Forrest, K., and Taylor, J. (2019). Australian rangeland futures: time now for systemic responses to interconnected challenges. *The Rangeland Journal* **41**, 271–292. doi:10.1071/RJ18105

Forsyth, D. M., Woolnough, A. P., Nimmo, D. G., Ritchie, E. G., Kennedy, M., Pople, A., and Watson, I. (2014). A comment on the influence of dingoes on the Australian sheep flock. *Australian Veterinary Journal* **92**, 461–462. doi:10.1111/avj.12277

Franks, A. J. (2002). The ecological consequences of Buffel Grass *Cenchrus ciliaris* establishment within remnant vegetation of Queensland. *Pacific Conservation Biology* **8**, 99–107. doi:10.1071/PC020099

Freudenberger, D., and Hacker, R. B. (1997). The effect of temporary closure of watering points on grazing intensity of red and grey kangaroos with related observations on feral goats. *The Rangeland Journal* **19**, 157–165. doi:10.1071/RJ9970157

Freudenberger, D., Wilson, A., and Palmer, R. (1999). The effects of perennial grasses, stocking rate and rainfall on sheep production in a semi-arid woodland of eastern Australia. *The Rangeland Journal* **21**, 199–219. doi:10.1071/RJ9990199

Fuhlendorf, S. D., Fynn, R. W. S., McGranahan, D. A., and Twidwell, D. (2017). Heterogeneity as the basis for rangeland management. *In*: 'Rangeland Systems: Processes, Management and Challenges'. (Ed. D. D. Briske.) pp. 169–196. (Springer Open: Cham, Switzerland.)

Fuls, E. (1992). Ecosystem modification created by patch-overgrazing in semi-arid grassland. *Journal of Arid Environments* **23**, 59–69. doi:10.1016/S0140-1963(18)30541-X

Fyfe, W. V. (1940). Report of the Royal Commission Appointed to Inquire into and Report upon the Financial and Economic Position of the Pastoral Industry in the Leasehold Areas in Western Australia. Government Printer, Perth, WA, Australia.

Fynn, R. W. S., Kirkman, K. P., and Dames, R. (2017). Optimal grazing management strategies: evaluating key concepts. *African Journal of Range & Forage Science* **34**, 87–98. doi:10.2989/10220119.2017.1347584

Gammage, B. (2012). 'The Biggest Estate on Earth: How Aborigines Made Australia.' (Allen and Unwin: Sydney, NSW, Australia.)

Garnaut, R. (2019). 'Super-power: Australia's Low-carbon Opportunity.' (La Trobe University Press, in conjunction with B Lack Inc.: Melbourne, Vic., Australia.)

Gergis, J. (2018). 'Sunburnt Country; The History and Future of Climate Change in Australia.' (Melbourne University Press: Melbourne, Vic., Australia.)

Glen, A. S., and Short, H. (2000). The control of dingos in New South Wales in the period 1883–1930 and its likely impact on their distribution and abundance. *Australian Zoologist* **31**, 432–442. doi:10.7882/AZ.2000.003

Graetz, R. D. (1986). A comparative study of sheep grazing a semi-arid saltbush pasture in two condition classes. *Australian Rangeland Journal* **8**, 46–56. doi:10.1071/RJ9860046

Grice, A. C. (2006). The impacts of invasive plant species on the biodiversity of Australian rangelands. *The Rangeland Journal* **28**, 27–35. doi:10.1071/RJ06014

Haby, N. A., and Brandle, R. (2018). Passive recovery of small vertebrates following livestock removal in the Australian rangelands. *Restoration Ecology* **26**, 174–182. doi:10.1111/rec.12542

Hacker, R. B. (1987). Species responses to grazing and environmental factors in an arid halophytic shrubland community. *Australian Journal of Botany* **35**, 135–150. doi:10.1071/BT9870135

Hacker, R. B. (1993). A brief evaluation of time control grazing. *In*: 'Proceedings of the Eighth Annual Conference of the Grassland Society of New South Wales'. (Ed. D. Michalk.) pp. 82–89. (Grassland Society of New South Wales: Orange, NSW, Australia.)

Hacker, R. B. (2010). Extensive grazing systems. *In*: 'International Sheep and Wool Handbook'. (Ed. D. Cottle.) pp. 507–532. (Nottingham University Press: Nottingham, UK.)

Hacker, R. B. (2013). Celebrating diversity: people, place and purpose. A synthesis of the 17th biennial conference of The Australian Rangeland Society. *The Rangeland Journal* **35**, 241–244. doi:10.1071/RJ13046

Hacker, R. B., and Alemseged, Y. (2014). Incorporating farmed goats into sustainable rangeland grazing systems in southern Australia: a review. *The Rangeland Journal* **36**, 25–33. doi:10.1071/RJ13035

Hacker, R. B., and Freudenberger, D. (1997). The effect of short-term exclosure of watering points on the behaviour and harvesting efficiency of grey and red kangaroos. *The Rangeland Journal* **19**, 145–156. doi:10.1071/RJ9970145

Hacker, R. B., and Hodgkinson, K. C. (1996). Implementing tactical grazing in whole property management. *In*: 'Rangelands in a Sustainable Biosphere: Proceedings of the Fifth International Rangeland Congress'. (Ed. N. E. West.) pp. 197–198. (Society for Range Management: Denver, CO.)

Hacker, R., and McLeod, S. (2003). 'Living with Kangaroos. A Guide to Kangaroos and their Management in the Murray–Darling Basin.' (NSW Agriculture.) ISBN 0 7347 1505 6.

Hacker, R. B., and Smith, W. J. (2007). An evaluation of the DDH/100mm stocking rate index and an alternative approach to stocking rate estimation. *The Rangeland Journal* **29**, 139–148. doi:10.1071/RJ07001

Hacker, R. B., Hodgkinson, K. C., Melville, G. J., Bean, J., and Clipperton, S. P. (2006*a*). Death model for tussock perennial grasses: thresholds for grazing-induced mortality of mulga Mitchell grass (*Thyridolepis mitchelliana*). *The Rangeland Journal* **28**, 105–114. doi:10.1071/RJ06001

Hacker, R. B., Alemseged, Y., Carberry, P. M., Browne, R. H., and Smith, W. J. (2006*b*). 'Betting on Rain.' (New South Wales Department of Primary Industries: Orange, NSW, Australia.)

Hacker, R. B., Jessop, P. J., Smith, W. J., and Melville, G. J. (2010). A ground cover-based incentive approach to enhancing resilience in rangelands viewed as complex adaptive systems. *The Rangeland Journal* **32**, 283–291. doi:10.1071/RJ10011

Hacker, R. B., Sinclair, K., and Waters, C. M. (2019*a*). Total grazing pressure: a defining concept for extensive pastoral systems in the southern rangelands of Australia. *The Rangeland Journal* **41**, 457–460. doi:10.1071/RJ19026

Hacker, R. B., Sinclair, K., and Pahl, L. (2019*b*). Prospects for ecologically and socially sustainable management of total grazing pressure in the southern rangelands of Australia. *The Rangeland Journal* **41**, 581–586. doi:10.1071/RJ20006

Hacker, R. B., Barclay, R. M., Brill, B. J., Curran, G. C., Norris, D. A., and Woods, G. R. (Undated). The Western Uplands Landsafe Management Project, N061, January 1990–December 1994. Final Report, Murray–Darling Basin Natural Resources Management Strategy. NSW Agriculture. ISBN 0 7310 5628 0.

Hamilton, J. S., Chilcott, C. R., and Savage, D. B. (2008). Contemporary livestock carrying capacities for pastoral properties in northern Australia: a methodology for integrating objective data on pasture growth and condition. *Australian Journal of Experimental Agriculture* **48**, 735–740. doi:10.1071/EA08035

Hansen, P. J. (2009). Effects of heat stress on mammalian reproduction. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* **364**, 3341–3350. doi:10.1098/rstb.2009.0131

Harrington, G. N. (1991). Effects of soil moisture on shrub seedling survival in a semi-arid grassland. *Ecology* **72**, 1138–1149. doi:10.2307/1940611

Harrington, G. N., Wilson, A. D., and Young, M. D. (Eds) (1984*a*). 'Management of Australia's Rangelands.' (CSIRO Publishing: Melbourne, Vic., Australia.)

Harrington, G. N., Mills, D. M. D., Pressland, A. J., and Hodgkinson, K. C. (1984*b*). Semi-Arid Woodlands. *In*: 'Management of Australia's Rangelands'. (Eds G. N. Harrington, A. D. Wilson and M. D. Young.) pp. 189–207. (CSIRO: Melbourne, Vic., Australia.)

Hart, Q., and Edwards, G. (2016). Outcomes of the Australian Feral Camel Management Project and the future of feral camel management in Australia. *The Rangeland Journal* **38**, 201–206. doi:10.1071/RJ15087

Hawkins, H. J. (2017). A global assessment of Holistic Planned Grazing™ compared with season-long, continuous grazing: meta-analysis findings. *African Journal of Range & Forage Science* **34**, 65–75. doi:10.2989/10220119.2017.1358213

Higgins, S. I., Kantelhardt, J., Scheiter, S., and Boerner, J. (2007). Sustainable management of extensively managed savanna rangelands. *Ecological Economics* **62**, 102–114. doi:10.1016/j.ecolecon.2006.05.019

Higgins, V., Dibden, J., Potter, C., Moon, K., and Cocklin, C. (2014). Payments for ecosystem services, neoliberalisation, and the hybrid governance of land management in Australia. *Journal of Rural Studies* **36**, 463–474. doi:10.1016/j.jrurstud.2014.10.003

Hodgkinson, K. C., and Harington, G. N. (1985). The case for prescribed burning to control shrubs in eastern semi-arid woodlands. *Australian Rangeland Journal* **7**, 64–74. doi:10.1071/RJ9850064

Holechek, J. L., Gomez, H., Molinar, F., and Galt, D. (1999). Grazing studies: what we've learned. *Rangelands* **21**, 12–16.

Holechek, J. L., Gomes, H., Molinar, F., Galt, D., and Valdez, R. (2000). Short-duration grazing: the facts in 1999. *Rangelands* **22**, 18–22. doi:10.2458/azu_rangelands_v22i1_holechek

Holm, A. McR., Watson, I. W., Loneragan, W. A., and Adams, M. A. (2003). Loss of patch-scale heterogeneity on primary productivity and rainfall-use efficiency in Western Australia. *Basic and Applied Ecology* **4**, 569–578. doi:10.1078/1439-1791-00187

Holm, A. McR., Watson, I. W., Speijers, E. J., Allen, R. J., Eliot, G. J., Shackleton, K. R., and Stretch, J. K. (2005). Loss of patch-scale heterogeneity on secondary productivity in the arid shrubland of Western Australia. *Journal of Arid Environments* **61**, 631–649. doi:10.1016/j.jaridenv.2004.09.014

Holmes, J. (2002). Diversity and change in Australia's rangelands: a post-productivist transition with a difference? *Transactions of the Institute of British Geographers* **27**, 362–384. doi:10.1111/1475-5661.00059

Holmes, P. R. (2015). Rangeland pastoralism: change and sustainability. *In*: 'Innovation in the Rangelands. Proceedings of the 18th Australian Rangeland Society Biennial Conference', Alice Springs, NT, Australia. (Ed. M. H. Friedel.) p. 5. (Australian Rangeland Society: Parkside, SA, Australia.)

Hosking, J. R., McFadyen, R. E., and Murray, N. D. (1988). Distribution and biological control of cactus species in eastern Australia. *Plant Protection Quarterly* **3**, 115–123.

Howden, S. M., Moore, J. L., McKeon, G. M., and Carter, J. O. (2001). Global change and the mulga woodlands of southwest Queensland: greenhouse gas emissions, impacts, and adaptation. *Environment International* **27**, 161–166. doi:10.1016/S0160-4120(01)00077-0

Hrdina, F. (1997). Marsupial destruction in Queensland 1877–1930. *Australian Zoologist* **30**, 272–286. doi:10.7882/AZ.1997.003

Hunt, L. P. (2001). Heterogeneous grazing causes local extinction of edible perennial shrubs: a matrix analysis. *Journal of Applied Ecology* **38**, 238–252. doi:10.1046/j.1365-2664.2001.00586.x

Hunt, L. P. (2003). Opportunities for the future in Australia's grazed rangelands. *The Rangeland Journal* **25**, 183–195. doi:10.1071/RJ03015

Hunt, L. P., McIvor, J. G., Grice, A. C., and Bray, S. G. (2014). Principles and guidelines for managing cattle grazing in the grazing lands of northern Australia: stocking rates, pasture resting, prescribed fire, paddock size and water points: a review. *The Rangeland Journal* **36**, 105–119. doi:10.1071/RJ13070

James, C. D. (2003). Response of vertebrates to fenceline contrasts in grazing intensity in semi-arid woodlands of eastern Australia. *Austral Ecology* **28**, 137–151. doi:10.1046/j.1442-9993.2003.01259.x

Johnson, J. S. (2018). Heat stress: impact on livestock well-being and productivity and mitigation strategies to alleviate the negative effects. *Animal Production Science* **58**, 1404–1413. doi:10.1071/AN17725

Johnston, P. W., McKeon, G. M., and Day, K. A. (1996*a*). Objective 'safe' grazing capacities for south-west Queensland Australia: development of a model for individual properties. *The Rangeland Journal* **18**, 244–258. doi:10.1071/RJ9960244

Johnston, P. W., Tannock, P. R., and Beale, I. F. (1996*b*). Objective 'safe' grazing capacities for south-west Queensland Australia: model application and evaluation. *The Rangeland Journal* **18**, 259–269. doi:10.1071/RJ9960259

Jones, R. J., and Sandland, R. L. (1974). The relationship between animal gain and stocking rate. Derivation of the relation from the results of grazing trials. *The Journal of Agricultural Science* **83**, 335–342. doi:10.1017/S0021859600052035

Jones, R., Saunders, G., and Balogh, S. (2006). An Economic Evaluation of a Pest Management Control Program: 'Outfox the Fox'. Economic Research Report No. 29. NSW Department of Primary Industries, Orange. Available at: http://www.agric.nsw.gov.au/reader/10550

Khairo, S. A., Hacker, R. B., Atkinson, T. L., and Turnbull, G. L. (2011). Economic analysis of feral goat control within the NSW rangeland. Report prepared for Western Catchment Management Authority. Economic Research Report No. 47. 56 pp. NSW Department of Trade and Investment, Regional Infrastructure and Services, Trangie, NSW, Australia.

Khairo, S. A., Hacker, R. B., Atkinson, T. L., and Turnbull, G. L. (2013). Alternative strategies for management of feral goats: implications for natural resource management policies in New South Wales rangelands. *The Rangeland Journal* **35**, 201–210. doi:10.1071/RJ13020

Landsberg, J., James, C. D., Morton, S. R., Hobbs, T. J., Stol, J., Drew, A., and Tongway, H. (1997). The effects of artificial sources of water on rangeland biodiversity. Final Report to the Biodiversity Conservation and Strategy Section of the Biodiversity Group, Environment Australia. Environment Australia and CSIRO.

Landsberg, R. G., Ash, A. J., Shepherd, R. K., and McKeon, G. M. (1998). Learning from history to survive in the future: management evolution on Trafalgar Station, north-east Queensland. *The Rangeland Journal* **20**, 104–118. doi:10.1071/RJ9980104

Landsberg, J., James, C. D., Morton, S. R., Müller, W. J., and Stol, J. (2003). Abundance and composition of plant species along grazing gradients in Australian rangelands. *Journal of Applied Ecology* **40**, 1008–1024. doi:10.1111/j.1365-2664.2003.00862.x

Lange, R. T., Nicholson, A. D., and Nicholson, D. A. (1984). Vegetation management of chenopod rangelands in South Australia. *The Rangeland Journal* **6**, 46–54. doi:10.1071/RJ9840046

Leigh, J. H., Wilson, A. D., and Mulham, W. E. (1968). A study of Merino sheep grazing a cotton-bush (*Kochia aphylla*)–grassland (*Stipa variabilis, Danthonia caespitosa*) community on the Riverine Plain. *Australian Journal of Agricultural Research* **19**, 947–961. doi:10.1071/AR9680947

Ludwig, J. A., and Tongway, D. J. (1997). A landscape approach to rangeland ecology. *In*: 'Landscape Ecology, Function and Management: Principles from Australia's Rangelands'. (Eds J. Ludwig, D. Tongway, D. Freudenberger, J. Noble and K. Hodgkinson.) pp. 1–12. (CSIRO Publishing: Melbourne, Vic., Australia.)

Lunney, D. (2001). Causes of the extinction of native mammals of the Western Division of New South Wales: an ecological interpretation of the nineteenth century historical record. *The Rangeland Journal* **23**, 44–70. doi:10.1071/RJ01014

MacLeod, N. D. (1990). Issues of size and viability of pastoral holdings in the Western Division of New South Wales. *Australian Rangeland Journal* **12**, 67–78. doi:10.1071/RJ9900067

Marshall, N. A. (2015). Adaptive capacity of the northern Australian rangelands. *The Rangeland Journal* **37**, 617–622. doi:10.1071/RJ15054

Marshall, G. R., and Stafford-Smith, D. M. (2010). Natural resources governance for the drylands of the Murray–Darling Basin. *The Rangeland Journal* **32**, 267–282. doi:10.1071/RJ10020

McCosker, T. (2000). Cell Grazing: the first 10 years in Australia. *Tropical Grasslands* **34**, 207–218.

McDonald, S. E., Reid, N., Waters, C. M., Smith, R., and Hunter, J. (2018). Improving ground cover and landscape function in a semi-arid rangeland through alternative grazing management. *Agriculture, Ecosystems & Environment* **268**, 8–14. doi:10.1016/j.agee.2018.08.021

McDonald, S. E., Lawrence, R., Kendall, L., and Rader, R. (2019*a*). Ecological, biophysical and production effects of incorporating rest into grazing regimes: a global meta-analysis. *Journal of Applied Ecology* **56**, 2723–2731. doi:10.1111/1365-2664.13496

McDonald, S. E., Reid, N., Smith, R., Waters, C. M., Hunter, J., and Rader, R. (2019*b*). Rotational grazing management achieves similar plant diversity outcomes to areas managed for conservation in a semi-arid rangeland. *The Rangeland Journal* **41**, 135–145. doi:10.1071/RJ18090

McDonald, S. E., Reid, N., Smith, R., Waters, C. M., Hunter, J., and Rader, R. (2020). Comparison of biodiversity and ground cover between a commercial rotationally grazed property and an adjacent nature reserve in semi-arid rangeland. *Austral Ecology* **45**, 60–69. doi:10.1111/aec.12829

McKeon, G. M., Hall, W. B., Henry, B. K., Stone, G. S., and Watson, I. W. (Eds) (2004). 'Pasture Degradation and Recovery in Australia's Rangelands: Learning from History.' (Queensland Department of Natural Resources, Mines and Energy: Indooroopilly, Qld, Australia.)

McKeon, G. M., Stone, G. S., Syktus, J. I., Carter, J. O., Flood, N. R., Ahrens, D. G., Bruget, D. N., Chilcott, C. R., Cobon, D. H., Cowley, R. A., Crimp, S. J., Fraser, G. W., Howden, S. M., Johnston, P. W., Ryan, J. G., Stokes, C. J., and Day, K. A. (2009). Climate change impacts on northern Australian rangeland livestock carrying capacity: a review of issues. *The Rangeland Journal* **31**, 1–29. doi:10.1071/RJ08068

McLeod, S. R., and Hacker, R. B. (2019). Balancing stakeholder interests in kangaroo management: historical perspectives and future prospects. *The Rangeland Journal* **41**, 567–579. doi:10.1071/RJ19055

Miller, G., Friedel, M., Adam, P., and Chewings, V. (2010). Ecological impacts of buffel grass (*Cenchrus ciliaris* L.) invasion in central Australia: does field evidence support a fire-invasion feedback? *The Rangeland Journal* **32**, 353–365. doi:10.1071/RJ09076

Moore, J. L., Howden, S. M., McKeon, G. M., Carter, J. O., and Scanlan, J. C. (2001). The dynamics of grazed woodlands in southwest Queensland, Australia and their effect on greenhouse gas emissions. *Environment International* **27**, 147–153. doi:10.1016/S0160-4120(01)00075-7

Morrissey, J. G., and O'Connor, R. E. Y. (1989). 28 years of station management, 'fair use and a fair go'. *W. A. Dept. of Agriculture Pastoral Memo (Carnarvon)* **13**, 2–9.

Morton, S. R. (1990). The impact of European settlement on the vertebrate animals of arid Australia: a conceptual model. *Proceedings of the Ecological Society of Australia* **16**, 201–213.

Morton, S. R., Stafford-Smith, D. M., Friedel, M. H., Griffin, G. F., and Pickup, G. (1995). The stewardship of arid Australia: ecology and landscape management. *Journal of Environmental Management* **43**, 195–217. doi:10.1016/S0301-4797(95)90402-6

Moseby, K. E., Neilly, H., Read, J. L., and Crisp, H. A. (2012). Interactions between a top order predator and exotic mesopredators in the Australian rangelands. *International Journal of Ecology* **2012**, 250352. doi:10.1155/2012/250352

Nicholson, A. D. (2017). 'Wizzo. The Story of a Well and the Nicholson Family.' (Openbook Howden Print and Design: Adelaide, SA, Australia.)

Nielsen, U. N., Stafford-Smith, M., Metternicht, G. I., Ash, A., Baumber, A., Boer, M. M., Booth, S., Burnside, D., Churchill, A. C., Hassan, M. E., Friedel, M. H., Goode, C. M., Kelly, D., Leys, J. F., McDonald, S. E., Maru, Y. T., Phelps, D. G., Ridges, M., Simpson, G., Traill, B., Walker, B., Waters, C. M., and Whyte, A. W. (2020). Challenges, solutions and research priorities for sustainable rangelands. *The Rangeland Journal* **42**, 359–373. doi:10.1071/RJ20059

Nix, H. A., and Austin, M. P. (1973). Mulga: a bioclimatic analysis. *Tropical Grasslands* **7**, 9–21.

Noble, J. C. (Undated). 'The Delicate and Noxious Scrub. CSIRO Studies on Native Tree and Shrub Proliferation in the Semi-Arid Woodlands of Eastern Australia.' (CSIRO)

Noble, I., Barson, M., Dumsday, R., Friedel, M., Hacker, R., McKenzie, N., Smith, G., Young, M., Maliel, M., and Zammit, C. (1996). Land resources. *In*: 'Australia: State of the Environment 1996'. pp. 6-1–6-55. (CSIRO Publishing: Melbourne, Vic., Australia.)

Norbury, G. L. (1992). An electrified watering trough that selectively excludes kangaroos. *The Rangeland Journal* **14**, 3–8. doi:10.1071/RJ9920003

Norbury, G. L., and Norbury, D. C. (1993). The distribution of red kangaroos in relation to range regeneration. *The Rangeland Journal* **15**, 3–11. doi:10.1071/RJ9930003

Norbury, G. L., Norbury, D. C., and Hacker, R. B. (1993). Impact of red kangaroos on the pasture layer in the Western Australian arid zone. *The Rangeland Journal* **15**, 12–23. doi:10.1071/RJ9930012

Northcote, K. H. (1979). 'A Factual Key for the Recognition of Australian Soils.' 4th edn. (Rellim Technical Publications: Adelaide, SA, Australia.)

Norton, B. (1998). The application of grazing management to increase sustainable livestock production. *Animal Production in Australia* **22**, 15–26.

Norton, B. E. (2003). Spatial management of grazing to enhance both livestock production and resource condition: a scientific argument. *In*: 'Proceedings of the VIIth International Rangeland Congress', 26 July–1 August, Durban, South Africa. (Eds N. Allsop, A. R. Palmer, S. J. Milton, H. P. Kirkman, G. J. H. Kerley, C. R. Hurt, C. J. and Brown.) pp. 810–820. (Grassland Society of Southern Africa.) ISBN 0-958-45348-9.

Novelly, P. E., and Warburton, D. (2012). A Report on the Viability of Pastoral Leases in the Southern Rangelands Pastoral Region Based on

Biophysical Assessment. Department of Agriculture and Food Western Australia. 44 pp.

Noy-Meir, I. (1973). Desert ecosystems: environment and producers. *Annual Review of Ecology and Systematics* **4**, 25–51. doi:10.1146/annurev.es.04.110173.000325

Orgill, S. E., Waters, C. M., Melville, G., Toole, I., Alemseged, Y., and Smith, W. (2017). Sensitivity of soil organic carbon to grazing management in the semi-arid rangelands of south-eastern Australia. *The Rangeland Journal* **39**, 153–167. doi:10.1071/RJ16020

Osborn, T. G. B., Wood, J. G., and Paltridge, T. B. (1932). On the growth and reaction to grazing of the perennial saltbush, *Atriplex vesicaria*: an ecological study of the biotic factor. *Proceedings of the Linnean Society of New South Wales* **57**, 377–402.

Pahl, L. (2019*a*). Macropods, feral goats, sheep and cattle. 2. Equivalency in what and where they eat. *The Rangeland Journal* **41**, 519–533. doi:10.1071/RJ19059

Pahl, L. (2019*b*). Macropods, feral goats, sheep and cattle. 1. Equivalency in how much they eat. *The Rangeland Journal* **41**, 497–518. doi:10.1071/RJ19044

Passmore, J. G. I., and Brown, C. G. (1992). Property size and rangeland degradation in the Queensland mulga rangelands. *The Rangeland Journal* **14**, 9–25. doi:10.1071/RJ9920009

Payne, A. L., Curry, P. J., and Spencer, G. F. (1987). 'An Inventory and Condition Survey of Rangelands in the Carnarvon Basin, Western Australia.' Technical Bulletin No. 73. (Department of Agriculture: Perth, WA, Australia.) ISSN 0083-867.

Payne, A. L., Mitchell, A. A., and Holman, W. F. (1988). 'An Inventory and Condition Survey of Rangelands in the Ashburton River Catchment, Western Australia.' Technical Bulletin No. 62. Revised edn. (Department of Agriculture: Perth, WA, Australia.) ISSN 0083-8675.

Pickup, G., and Stafford-Smith, M. (1993). Prospects and procedures for assessing the sustainability of pastoral land management in Australia. *Journal of Biogeography* **20**, 471–487. doi:10.2307/2845721

Polley, H. W., Mayeux, H. W., Johnson, H. B., and Tischler, C. R. (1997). Viewpoint: atmospheric CO_2, soil water, and shrub/grass ratios on rangelands. *Journal of Range Management* **50**, 278–284. doi:10.2307/4003730

Powell, O., Silcock, J., and Fensham, R. (2015). Oases to oblivion: the rapid demise of springs in the south-eastern Great Artesian Basin, Australia. *Ground Water* **53**, 171–178. doi:10.1111/gwat.12147

Pringle, H. J. R., and Tinley, K. L. (2003). Are we overlooking critical geomorphic determinants of landscape change in Australian rangelands? *Ecological Management & Restoration* **4**, 180–186. doi:10.1046/j.1442-8903.2003.00154.x

Pringle, H. J. R., Watson, I. W., and Tinley, K. L. (2006). Landscape improvement, or ongoing degradation – reconciling apparent contradictions from the arid rangelands of Western Australia. *Landscape Ecology* **21**, 1267–1279. doi:10.1007/s10980-006-0015-x

Purvis, J. R. (1986). Nurture the land: my philosophies of pastoral management in central Australia. *Australian Rangeland Journal* **8**, 110–117. doi:10.1071/RJ9860110

Read, J. L., and Cunningham, R. (2010). Relative impacts of cattle grazing and feral animals on an Australian arid zone reptile and small mammal assemblage. *Austral Ecology* **35**, 314–324. doi:10.1111/j.1442-9993.2009.02040.x

Reid, J., and Fleming, M. (1992). The conservation status of birds in arid Australia. *The Rangeland Journal* **14**, 65–91. doi:10.1071/RJ9920065

Revell, D. K., Maynard, B., Erkelenz, P. A., and Thomas, D. T. (2015). Rangeland self-herding – positively influencing grazing distribution to benefit livestock, landscapes and people. *In*: 'Proceedings of the 18th Australian Rangeland Society Biennial Conference'. (Ed. M. H. Friedel.) (Australian Rangeland Society: Perth.) https://austrangesoc.com.au/wp-content/uploads/2021/01/ARS_2015_3.08.-Revell-et-al.pdf

Reynolds, J. F., Smith, D. M. S., Lambin, E. F., Turner, B. L., Mortimore, M., Batterbury, S. P. J., Downing, T. E., Dowlatabadi, H., Fernández, R. J., Herrick, J. E., Huber-Sannwald, E., Jiang, H., Leemans, R., Lynam, T., Maestre, F. T., Ayarza, M., and Walker, B. (2007). Global desertification: building a science for dryland development. *Science* **316**, 847–851. doi:10.1126/science.1131634

Rickert, K. G. (1996). Stocking rate and sustainable grazing systems. *Wageningen Agricultural University Papers* **96–4**, 29–65.

Ridges, M., Kelly, M., Simpson, G., Leys, J., Booth, S., Friedel, M., and Country, N. (2020). Understanding how Aboriginal culture can contribute to the resilient future of rangelands: the importance of Aboriginal core values. *The Rangeland Journal* **42**, 247–251. doi:10.1071/RJ20031

Roe, R., and Allen, G. H. (1993). Studies on the Mitchell grass association in south-western Queensland. 3. Pasture and wool production under different rates of stocking and continuous or rotational grazing. *The Rangeland Journal* **15**, 302–319. doi:10.1071/RJ9930302

Roshier, D. A., and Barchia, I. (1993). Relationships between sheep production, stocking rate and rainfall on commercial sheep properties in western New South Wales. *The Rangeland Journal* **15**, 79–93. doi:10.1071/RJ9930079

Roshier, D. A., and Nichol, H. I. (1998). Implications of spatio-temporal variation in forage production and utilisation for animal productivity in extensive grazing systems. *The Rangeland Journal* **20**, 3–25. doi:10.1071/RJ9980003

Sanderman, J., Reseigh, J., Wurst, M., Young, M. A., and Austin, J. (2015). Impacts of rotational grazing on soil carbon in native grass-based pastures in southern Australia. *PLoS One* **10**, e0136157. doi:10.1371/journal.pone.0136157

Sanjari, G., Ghadiri, H., Ciesiolka, C. A., and Yu, B. (2008). Comparing the effects of continuous and time-controlled grazing systems on soil characteristics in Southeast Queensland. *Soil Research* **46**, 348–358. doi:10.1071/SR07220

Sanjari, G., Ghadiri, H., and Yu, B. (2016). Effects of time-controlled and continuous grazing on total herbage mass and ground cover. *Journal of Agriculture and Rural Development in the Tropics and Subtropics* **117**, 165–174.

Saunders, D., and Curry, P. (1990). The impact of agricultural and pastoral industries on birds in the southern half of Western Australia: past, present and future. *Proceedings of the Ecological Society of Australia* **16**, 303–321.

Savory, A. (1983). The Savory grazing method or holistic resource management. *Rangelands* **5**, 155–159.

Savory, A. (2013). How to fight desertification and reverse climate change. TED Talk. Available at: https://www.ted.com/talks/allan_savory_how_to_green_the_world_s_deserts_and_reverse_climate_change [accessed June 2020].

Silcock, J. L., and Fensham, R. J. (2013). Arid vegetation in disequilibrium with livestock grazing: evidence from long-term exclosures. *Austral Ecology* **38**, 57–65. doi:10.1111/j.1442-9993.2012.02374.x

Silcock, J. L., and Fensham, R. J. (2019). Degraded or just dusty? Examining ecological change in arid lands. *Bioscience* **69**, 508–522. doi:10.1093/biosci/biz054

Silcock, J. L., Healy, A. J., and Fensham, R. J. (2014). Lost in time and space: re-assessment of conservation status in an arid-zone flora through targeted field survey. *Australian Journal of Botany* **62**, 674–688. doi:10.1071/BT14279

Sinclair, K., Curtis, A. L., Atkinson, T., and Hacker, R. B. (2019*a*). Public attitudes to animal welfare and landholder resource limitations: implications for total grazing pressure management in the southern rangelands of Australia. *The Rangeland Journal* **41**, 477–484. doi:10.1071/RJ19046

Sinclair, K., Curtis, A. L., Hacker, R. B., and Atkinson, T. (2019*b*). Stakeholder judgements of the social acceptability of control practices for kangaroos, unmanaged goats and feral pigs in the south-eastern rangelands of Australia. *The Rangeland Journal* **41**, 485–496. doi:10.1071/RJ19047

SRM Glossary (Society for Range Management) (2020). Available at: https://globalrangelands.org/glossary?term= [accessed 24 July 2020].

Stafford Smith, D. M., and McAllister, R. R. J. (2008). Managing arid zone natural resources in Australia for spatial and temporal variability: an approach from first principles. *The Rangeland Journal* **30**, 15–27. doi:10.1071/RJ07052

Stafford-Smith, D. M., Morton, S. R., and Ash, A. J. (2000). Towards sustainable pastoralism in Australia's rangelands. *Australasian Journal of Environmental Management* **7**, 190–203. doi:10.1080/14486563.2000.10648501

Stafford Smith, D. M., McKeon, G. M., Watson, I. W., Henry, B. K., Stone, G. S., Hall, W. B., and Howden, S. M. (2007). Learning from episodes of degradation and recovery in variable Australian rangelands. *Proceedings of the National Academy of Sciences of the United States of America* **104**, 20690–20695. doi:10.1073/pnas.0704837104

Stone, G. S. (2004). Analysis of grazing pressure from the long-term livestock records of two western Queensland pastoral properties. *In*: 'Pasture Degradation and Recovery in Australia's Rangelands: Learning from History'. (Eds G. M. McKeon, W. B. Hall, B. K. Henry, G. S. Stone and I. W. Watson.) pp. 191–235. (Queensland Department of Natural Resources, Mines and Energy: Indooroopilly, Qld, Australia.)

Teague, R., Provenza, F., Norton, B., Steffens, T., Barnes, M., Kothmann, M., and Roath, R. (2008). Benefits of multi-paddock grazing management on rangelands: limitations of experimental grazing research and knowledge gaps. *In*: 'Grasslands: Ecology, Management and Restoration'. (Ed. H. G. Schroder.) pp. 41–80. (Nova Science Publishers: Hauppauge, NY, USA.)

Teague, R., Provenza, F., Kreuter, U., Steffens, T., and Barnes, M. (2013). Multi-paddock grazing on rangelands: why the perceptual dichotomy between research results and rancher experience? *Journal of Environmental Management* **128**, 699–717. doi:10.1016/j.jenvman.2013.05.064

Tiver, F., and Andrew, M. H. (1997). Relative effects of herbivory by sheep, rabbits, goats and kangaroos on recruitment and regeneration of shrubs and trees in eastern South Australia. *Journal of Applied Ecology* **34**, 903–914. doi:10.2307/2405281

Tongway, D. J., and Ludwig, J. A. (1997). The nature of landscape dysfunction in rangelands. *In*: 'Landscape Ecology, Function and Management: Principles from Australia's Rangelands'. (Eds J. Ludwig, D. Tongway, D. Freudenberger, J. Noble and K. Hodgkinson.) pp. 49–61. (CSIRO Publishing: Canberra, ACT, Australia.)

Tothill, J. C., and Gillies, C. (1992). The pasture lands of northern Australia. Occasional Paper No. 5. Tropical Grasslands Society of Australia.

Tupper, G. (1978). Sheep production on a *Danthonia caespitosa-Stipa variabilis* grassland in response to fertilizers and deferred grazing. *Australian Journal of Experimental Agriculture* **18**, 210–217. doi:10.1071/EA9780210

URS (2004). Final evaluation of the Gascoyne-Murchison strategy: final report prepared for Department of Agriculture and The Board, Gascoyne–Murchison Strategy.

URS (2013). Final Report. Sustainable land use and economic development opportunities in the Western Australian Rangelands. Report prepared for Department of Agriculture and Food.

URS (2015). Evaluation of the WEST 2000 Plus Program. Report prepared for Western Local Land Services by URS Australia Pty Ltd, 22 May 2015.

van Etten, E. J. B. (2009). Inter-annual Rainfall Variability of Arid Australia: greater than elsewhere? *The Australian Geographer* **40**, 109–120. doi:10.1080/00049180802657075

van Etten, E. J. B. (2013). Changes to land tenure and pastoral lease ownership in Western Australia's central rangelands: implications for co-operative, landscape-scale management. *The Rangeland Journal* **35**, 37–46. doi:10.1071/RJ11088

van Klinken, R. D., and Friedel, M. H. (2017). Unassisted invasions: understanding and responding to Australia's high-impact environmental grass weeds. *Australian Journal of Botany* **65**, 678–690. doi:10.1071/BT17152

Ward, D. (2010). A resource ratio model of the effects of changes in CO_2 on woody plant invasion. *Plant Ecology* **209**, 147–152. doi:10.1007/s11258-010-9731-z

Waters, C. M., Orgill, S. E., Melville, G. J., Toole, I. D., and Smith, W. J. (2017). Management of grazing intensity in the semi-arid rangelands of southern Australia: effects on soil and biodiversity. *Land Degradation & Development* **28**, 1363–1375. doi:10.1002/ldr.2602

Waters, C., Reseigh-O'Brien, J., Pahl, L., Atkinson, T., Burnside, D., and Revell, D. (2018). Addressing feed supply and demand through total grazing pressure management. NSW Department of Primary Industries. p.173.

Waters, C. M., McDonald, S. E., Reseigh, J., Grant, R., and Burnside, D. G. (2019). Insights on the relationship between total grazing pressure management and sustainable land management: key indicators to verify impacts. *The Rangeland Journal* **41**, 535–556. doi:10.1071/RJ19078

Watson, I. W., and Novelly, P. E. (2012). Transitions across thresholds of vegetation states in the grazed rangelands of Western Australia. *The Rangeland Journal* **34**, 231–238. doi:10.1071/RJ11073

Watson, I. W., Holm, A. McR., Shackleton, K. R., and Allen, R. J. (1988). The effect of sheep stocking rate on red kangaroo grazing pressure. *In*: 'Working papers of the 5th Biennial Australian Rangeland Society Conference', June 1988, Longreach, Qld., Australia. pp. 62–65. (Australian Rangeland Society: Perth.)

Watson, I. W., Burnside, D. G., and Holm, A. McR. (1996). Event-driven or continuous: which is the better model for managers? *The Rangeland Journal* **18**, 351–369. doi:10.1071/RJ9960351

Watson, I. M., Westoby, M., and Holm, A. McR. (1997). Demography of two shrub species from an arid gazed ecosystem in Western Australia 1983–93. *Journal of Ecology* **85**, 815–832. doi:10.2307/2960604

Watson, I. W., Richardson, J., Thomas, P., and Shepherd, D. (2005). Change in the rangelands of the Gascoyne–Murchison. *Range Management Newsletter* **5**(3), 1–9.

Watson, I. W., Thomas, P. W. E., and Fletcher, W. J. (2007). The first assessment, using a rangeland monitoring system, of change in shrub and tree populations across the arid shrublands of Western Australia. *The Rangeland Journal* **29**, 25–37. doi:10.1071/RJ07018

Western Australian Herbarium (1998). FloraBase: the Western Australian Flora. Department of Biodiversity, Conversation and Attractions. Available at: https://florabase.dpaw.wa.gov.au/browse/profile/22872 [accessed 20 January 2021].

White, M. (2016). New AEGIC (Australian Export Grains Innovation Centre) maps show dramatic shift in Australia's rainfall zones since 2000. Available at: https://www.aginnovators.org.au/news/new-aegic-maps-show-dramatic-shift-australias-rainfall-zones-2000 [accessed 22 May 2020].

Wilson, A. D. (1979). Management of natural pastures of south-western New South Wales. *Australian Rangeland Journal* **1**, 351–362. doi:10.1071/RJ9790351

Wilson, A. D. (1991*a*). The influence of kangaroos and forage on sheep productivity in the semi-arid woodlands. *The Rangeland Journal* **13**, 69–80. doi:10.1071/RJ9910069

Wilson, A. D. (1991*b*). Forage utilization by sheep and kangaroos in a semi-arid woodland. *The Rangeland Journal* **13**, 81–90. doi:10.1071/RJ9910081

Wilson, G. R., and Edwards, M. (2019). Professional kangaroo population control leads to better animal welfare, conservation outcomes and avoids waste. *Australian Zoologist* **40**, 181–202. doi:10.7882/AZ.2018.043

Wilson, A., and Freebairn, A. (2017) Pastoralists as conservation providers: a new stewardship incentive mechanism for the South Australian rangelands. *In*: 'Proceedings of the 19th Australian Rangeland Society Biennial Conference'. (Australian Rangeland Society: Australia.)

Wilson, A. D., and Leigh, J. H. (1970). Comparisons of the productivity of sheep grazing natural pastures of the Riverine Plain. *Australian Journal of Experimental Agriculture and Animal Husbandry* **10**, 549–553. doi:10.1071/EA9700549

Wilson, A. D., and MacLeod, N. D. (1991). Overgrazing: present nor absent? *Journal of Range Management* **44**, 475–482. doi:10.2307/4002748

Wilson, S., and Swan, G. (2017). 'A Complete Guide to Reptiles of Australia.' (Reed New Holland: Sydney, NSW, Australia.)

Wilson, G., Dexter, N., O'Brien, P., and Bomford, M. (1992). 'Pest Animals in Australia. A Survey of Introduced Wild Animals.' (Bureau of Rural Resources.)

Wilson, G., Edwards, M., and Byron, N. (2020). Custodianship of wildlife on private land to support conservation: an Australian model. *The Rangeland Journal* **42**, 309–321. doi:10.1071/RJ20039

Windh, J. L., Ritten, J. P., Derner, J. D., Paisley, S., and Lee, B. (2020). Effects of long-term cattle market conditions on continuous season-long and rotational grazing system revenues. *The Rangeland Journal* **42**, 227–231. doi:10.1071/RJ20067

Witt, G. B., Harrington, R. A., and Page, M. J. (2009). Is 'vegetation thickening' occurring in Queensland's mulga lands: a 50-year aerial photographic analysis. *Australian Journal of Botany* **57**, 572–582. doi:10.1071/BT08217

WLLS (Western Local Land Services) (2019). Managing invasive native scrub. State of New South Wales through Local Land Services.

Woinarski, J. C. Z., and Fisher, A. (2003). Conservation and the maintenance of biodiversity in the rangelands. *The Rangeland Journal* **25**, 157–171. doi:10.1071/RJ03013

Woods, G. (1992). Property and Grazing Management. *In*: 'Rangeland Management in Western New South Wales'. (Ed. I. Simpson.) pp. 40–53. (NSW Agriculture: Orange, NSW, Australia.) ISBN 0 7305 6589 0.