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TOWARDS SUSTAINABLE GRASSLAND AND LIVESTOCK MANAGEMENT

Running head: Sustainable grassland & livestock management (Journal of Agricultural Science, Cambridge, 2007)

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SUMMARY

Grasslands are one of the world's major ecosystems groups and over the last century their use has changed from being volunteer leys, or a resource on non-arable land, to a productive resource equal to any crop and managed as such. Many grasslands are now being acknowledged as having a multi-functional role in producing food and rehabilitating crop lands, in environmental management and cultural heritage. However, grasslands across the globe are under increasing pressure from increasing human populations, reduced areas with increasing livestock numbers, declining terms of trade for livestock production, and they are managed to varying degrees of effectiveness. The complexity of grassland uses and the many aspects of grassy ecosystems require a framework wherein solutions for better management can be developed. The present paper discusses a generic approach to grassland management to satisfy these multiple objectives. A focus on ecosystem functionality, i.e. on water, nutrient and energy cycling and on the biodiversity required to sustain those functions provides a means of resolving the dilemmas faced, through the intermediary, management related, criteria of herbage mass, which also relates directly to animal production. Emphasis is placed on the opportunities to satisfy multiple objectives. A consideration of the basic relationships between stocking rate and animal production shows that the longer-term, economically optimal stocking rate is associated with improved environmental outcomes. There may be environmental objectives that go beyond economically sustainable limits for livestock producers and in those cases direct payments from Government or others will be needed. These are likely to be where degradation is clearly apparent. The achievement of desirable outcomes in grassland management that satisfy multiple objectives will require new areas of research that seek viable solutions for farmers and society.

INTRODUCTION

Throughout human history grasslands have been used to produce livestock for food, fibre and fuel. Grasslands also improve organic matter, utilized by crops and a range of plants used as medicines. Initially, gatherers and hunters took a wild harvest from natural ecosystems, but from around 10 000 BC large animals were domesticated and grazed on native grasslands to guarantee food supplies for developing communities with expanding populations. To support domesticated herds, people learned to store hay for difficult times, which in turn led to the selection, domestication and sowing of specific purpose forages to provide reliable feed supplements used to sustain increasingly intensified systems where livestock spend most or all of their life in pens. While intensive production systems can now be found in every county, the majority of the world's livestock still depend upon naturalized grasslands for part of their feed requirements. However, the intensive approaches that gained momentum in the 19th century along with industrialization created a pipeline factory mentality for grassland management where inputs were pumped in at the start and products trucked out at the end. This farm factory approach has led to major gains in productivity, but is not without major problems.

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The use of nitrogen fertilizer on grass pastures, for example, has dramatically changed productivity. However, the global impacts of high levels of energy use in N fertilizer manufacture to local impacts of nitrate pollution of waterways and ground water have environmental and social consequences. Today, increasing social concern about the adverse impacts of agricultural practices have led to increasing regulation of on-farm activities to meet society demands to restore some of the amenities of our landscape. This poses significant challenges for today's practitioners, farmers and scientists, many of whom grew up in the era of rapidly increasing productivity. Environmental issues are assuming an increasing importance in the practice of agriculture but with increasing human populations and increasingly scarce resources, dealing with these issues will require increasing inputs of time, funds and innovation. The present paper aims to review how livestock grazing systems that are primarily dependent upon grasslands are now being re-designed to link production with environmental management so that the multi-functionality desired of today's grasslands is achieved.

Grasslands (in the present paper, this term includes all those forage systems used by grazing livestock) occupy large areas of the world's 117 million km^2 of vegetated lands and provide forage for over 1800 million livestock units (World Resources Institute 2000) as well as wildlife populations. Grasslands encompass the savannas of Africa, the grasslands of Australia, the cerrado and campo of South America, the prairies of North America, and the steppes of Central Asia. In Central Europe, natural grasslands are almost absent and remnant reserves are anthropogenic and need management to inhibit reversion to forests (Tscharntke *et al.* 2005). Grasslands are a major natural resource used not only for the production of food, fibre, fuel and medicines to support more than 800 million people, but are critical for maintaining a favourable global environment. Today, however, rapidly increasing human populations are exerting such pressure on grassland resources that we cannot continue to simply further maximize production as in the past. As climate change, food scarcity, water scarcity, air contamination, grassland depletion and loss of biodiversity emerge as major constraints, the challenge is to better understand the multi-functionality of grassland, to improve the ecosystem services upon which all living organisms rely and to enhance environmental values through a change from thinking of the 'farm as a factory' to thinking of the 'farm as a managed, harvested ecosystem'. As Weiner (2003) pointed out, the central difference is that the factory model is self-delimiting with many of the factors that influence production considered to be externalities with which the farm does not interact. For the ecosystem model, there are fewer externalities because more of the factors affecting production, including many aspects of the environment, are considered to be within the agroecosystem.

The objective of the present paper is to discuss ways of responding to this paradigm shift, where management embraces ecosystem manipulation within a landscape context rather than a simple production focus at the farm scale. Some of the important questions related to this scaling-up challenge include the following: what levels of utilization from grasslands enable the maintenance or enhancement of the environmental values of grasslands? What are the opportunities to improve the grassland environment when much of the world's grasslands are overgrazed? Overgrazing/over-utilization arguably applies where herbivore consumption rates exceed growth and/or recovery rates of desirable plant species and the grassland ecosystem function as a whole is impaired and degraded, resulting in declining productivity over time, both of which reduce environmental values. What strategies are needed to resolve how best to satisfy production and environment goals? Are these problems technical or social? These dilemmas are complex because grasslands are productive natural resources and part of the environment that interacts with other environmental processes at regional (e.g. water production) and global (e.g. climate change) scales. The ultimate challenge is to devise management strategies that utilize grassland resources in a sustainable manner.

Throughout the last century, the Journal of Agricultural Science, Cambridge has been in the forefront of presenting research that has sought to understand and improve the productivity of grassland livestock systems (e.g. Middleton 1905; Armstrong 1907; Stapleton & Jenkins 1916). The present paper discusses some of the trends that today are being considered in developing sustainable management systems in both natural and sown grasslands. Emphasis is placed on general principles that underpin the development of grassland/livestock systems that are productive and environmentally sustainable.

The paper is written from a farm-centred environmental perspective, looking back at grazing livestock systems to see what may need to change in order for grasslands to remain productive and at the same time to enhance the environment. Since optimal solutions are not readily available for many issues, the starting point is to first discuss the services grasslands provide and then the framework within which farmers operate.

Grassland categories and services

To investigate where it is possible to integrate management for production and environmental goals, it is necessary to first identify the types of systems that must be considered. In broad terms, many grassland areas could be triaged into three very general categories:

- *Healthy or marginal*: Those areas where grasslands are predominately in a native or naturalized state; where there are minimal or readily manageable environmental threats; where current levels of production are appropriate and can be maintained with current knowledge and policies, and without the need for dramatic interventions. The focus can be more on environmental management than on production.
- *Disturbed:* Those areas where more intensive practices often apply; where the stable species base is reasonable, but could be improved, and more careful management is required to minimize nutrient and water leakage. Knowledge may be insufficient to achieve a good long-term balance between the environment and production; the area needs attention but is still retrievable within the current economic and political frameworks. Production values are emphasized over environmental issues, but significant environmental benefits can be obtained.
- *Dying*: Very disturbed areas, often subject to intense use, where production may focus on survival rather than commercial output; where there may be an almost complete absence of stable plant species and a high risk of adverse effects on the neighbouring environment through dust storms and/or stream pollution. Such areas may not be realistically restored to an environmentally acceptable state unless significant transfer payments are made or higher commodity prices paid by other sectors of society, even though they may still produce significant quantities of livestock products. Where production remains a dominant goal, environmental management objectives may be directed more toward preventing adverse impacts on neighbours.

The third category is problematic and requires society to accept the rehabilitation costs in return for the environmental benefits gained. For example, this would include re-designing livestock enterprises to incorporate more intensive systems that are highly productive with linkages to cropping systems and in consequence reduce the need to over-use the other categories of grasslands, i.e. the environmental costs of these systems becomes a net benefit for the less degraded systems. Feedlots are another obvious case. The main environmental need in these systems may be to simply limit the external impacts such as nutrients leaching and odours from the system. This category may be where society needs to accept that it is impossible to eliminate some of these negative impacts and recognise them as part of providing food, fibre, fuel and medicines for ever-increasing human populations. It would not be practical to restore highly degraded grasslands to the diversity and amenity value of traditional meadows. To continue to provide food for the world's ever-increasing population will require acknowledgement of a cost in terms of some continued adverse impacts from the more intensively used grasslands. An extreme example of categorizing landscapes based on health is cities, which are enormously expensive ecological disasters.

Applying this concept to categorizing grassland management may be a way forward. In reality, this is already taking place by incorporating the more 'pristine' areas into national park networks and subsidizing farmers in some countries to manage such areas on their farms. In contrast, the more intensively used grasslands are being subjected to increased regulation and policing to prevent damage to surrounding environments. If this concept is applied to grassland research, then the area of highest priority may be the 'disturbed' category, i.e. those areas where the environmental values can be enhanced and where levels of production can either be sustained or even enhanced, cost-effectively. Since this 'disturbed' category is currently less regulated, the prospects of developing better practices that meet production and environmental objectives within a self-regulated policy framework are good. Unfortunately, many grassland policies focus on the extremes of the spectrum due to a sense of emergency to protect 'healthy' or pristine grasslands (Sutherland 2002) and to rehabilitate 'dying' grasslands by imposing over-simplified strategies such as reducing livestock numbers or re-seeding vegetation.

In the present paper, the major emphasis is placed upon the 'disturbed' category because the authors believe that is where current research is most likely to deliver substantial benefits in acceptable time-frames by empowering land managers with knowledge to modify their current practices to incorporate multiple-use goals. Only recently have ecologists acknowledged the conservation value of these areas with different disturbance regimes (Tscharntke *et al.* 2005). From a global perspective, 'disturbed' grasslands will continue to be a major source of livestock products in many parts of the world (Sincich 2002).

A consideration of the range of services provided by grasslands is useful in assessing management practices. Up until the latter part of the 20th century, the provision of food, fibre, fuel and medicines were considered to be the primary services from grasslands. However, in the last 30 years, animal and plant biodiversity has been increasingly valued *per se*, and also for their contribution to maintaining the nutrient, water and energy flows which are recognized as a significant ecosystem service that underpins the functionality of grassland ecosystems. Additional services emerging as crucial in the 21st century are the globally important roles of grasslands in improving air quality, sequestering carbon, supporting pollinating and symbiotic organisms and other processes that maintain or repair ecosystems and landscapes. Unfortunately, much of the research through the last century concentrated on grasslands as a production system rather than as an ecosystem and the multi-services that grasslands provide were often ignored. Where productivity must be sustained over the long-term, the key issue is now how best to use grassland resources without causing deleterious effects to the environment, or decreasing incomes. To achieve this requires more integrated thinking about the processes operative in grassland ecosystems. Since decision-making typically devolves onto farmers, it is crucial to identify the factors that influence them.

Do farmers aim to maximize product or profit?

The productivity of grasslands and the environmental consequences are often influenced in the first instance by the attitudes of farmers. Do they have short or long-term goals? Do they want social status and, or a profitable business? Do they see themselves as nurturing the landscape or simply exploiting a resource; sometimes out of necessity? In the past, management has been treated simply as a technical issue, but the reality is that farming is done in a social context and profit is only one of many goals. Farmers often seek maximum productivity even if it is not profitable. In many cultures, farmers aim to maximize the number of animals/ha (as a measure of wealth) or the size of their animals (for show or as a demonstration of success) or the total animal product/ha (almost irrespective of cost). Production focused solely on animal number or performance inevitably leads to high grazing pressures and grassland degradation.

Using profit as the main driver of production does not always guarantee success and may also result in declining grassland condition. This occurs because many financial analyses do not include all the direct and indirect costs associated with production, but rely on simplified gross margins which often give a false estimate of the actual profit. To date, the costs of any environmental damage or rehabilitation programmes are rarely included in farm budgets. Moving grassland-based livestock production to a sustainable basis requires a change in culture within both the industry and the broader community, where environmental and social values added from an action are as significant in assessing its worth to the nation as the economic value it brings. Ways of integrating these objectives are still being incorporated into the concept we know as the 'triple bottom line' (TBL) or 'sustainability' reporting that is becoming an increasing common activity of large companies and small businesses alike to build trust and demonstrate accountability (Higgins 2001).

Vanclay (2004) proposes 27 principles that govern farmer decision-making behaviour; a subset relevant to the present paper is:

- 'It is hard to be green when you are in the red'; environmental management costs money.
- 'Doing the right thing' is a strong motivational factor; what is 'right' is a social construct.
- Farmers don't distinguish environmental issues from other farm management issues; they are all part of managing the farm.
- Sustainability means staying on the farm; the concept of sustainability often has a strong social component – passing on the farm to the next generation is a central issue. That requires retaining the resource base and land tenure from one generation to the next.
- Non-adoption of 'good' practices may reflect the fact that past recommendations were not good; can we guarantee that new recommendations will work any better?
- Farmers construct their own knowledge; practices need to be tailored to their frameworks.
- Farmers need to feel valued, particularly if society wants them to adopt more sustainable practices that may not make more money.

Applying these principles to better recommendations for grassland management is a difficult task. They illustrate the need to consider the social context within which farming occurs and the ways that managing for the environment and production need to align.

Environment and society

The environment is rated as a significant issue in developed countries and is becoming more important in others due to the realization that environmental problems have world-wide consequences such as global warming. This increasing community concern provides further impetus for farmers to voluntarily incorporate environmental values into their management objectives. However, while the general importance of the environment in developed countries is evident in surveys, management practices to address these issues are often based on studies that fail to take into account the effects and implications for the human sector (Batisse 1986), despite the fact that human impact is important, not only as a factor of degradation, but also as a factor of environmental recovery. The challenge is to find approaches to environmental management that give people the quality of life they seek while protecting the environmental systems that underpins society's well being. Resolving this dilemma is difficult as society's 'wants' are often based on ignorance about (a) how food production occurs (b) ecological and environmental processes, (c) what would happen if you do, or do not, manage the land, (d) the view that farming is either idyllic or too hard, (e) the view of the countryside as 'the bits you drive through between the cities' or 'the bit I go to for recreation' and want to look 'nice'.

In Australia, for example, members of the public rank the environment third behind family and friends as an issue of importance, ahead of leisure (which includes sport) service to others, work, religion or politics (Young 2003). The general picture is that the public is concerned about the need for a clean environment and many are willing to personally pay for environmental services, whereas others see government and industry as responsible for funding farmers to implement environmental programmes. This suggests that agriculture has measured societal support provided it develops more environmentally friendly management practices. Similar attitudes apply in Europe, where policies of the European Union and the Common Agricultural Policy strongly support environmental management (Hall *et al.* 2004). However, given that farmers do not necessarily distinguish between environment and farm issues (Vanclay 2004), better environmental practices on farms need to be developed as part of production systems. The large sectors of society that live in cities need to appreciate that environmental impacts in grassland systems are more difficult to control or reverse than is the case in urban areas. Reconnecting urban dwellers to the countryside through awareness and education programs, if appropriately done, could help resolve some environmental dilemmas.

Productivity, profits and the environment

Productivity is considered by many to be the engine that drives overall wellbeing with higher rates of growth in productivity most benefiting society. The need to simultaneously maintain productivity, profitability and the environment is becoming the major interaction that farmers seek to resolve. Intensification has been a major driver of productivity increases from grassland systems. However, arguably environmental risks and costs increase with intensification, as does the level of disturbance and utilization of grasslands, leading to loss of soil resources which increases costs of replacing nutrients and species and in managing nutrient runoff.

Just as importantly, high utilization rates and levels of productivity may not always be the most profitable. This is illustrated with the relative economics of sheep for wool production on grasslands in central New South Wales Australia, using a gross-margin model (Vere *et al.* 1993). A comparison was carried out between resowing a degraded pasture with introduced species (*Phalaris* spp. and *Trifolium subterraneum*) or managing the grassland to a more productive state with a combination of fertilizer, strategic rest and conservative stocking rate (Figure 1).

In each case, it was assumed that maximum stocking rates would be reached by year three in order to optimize the proportion of perennial grasses and improve the likely longevity of the pasture (Michalk *et al.* 2003*b*). The alternate pathway shown in Fig. 1 (dotted line) is likely to be more typical of farms in the region as farmers report that the productivity of sown pastures declines significantly over time (Reeve *et al.* 2000). High levels of grazing pressure/utilization result in the loss of more productive species, except in areas where the natural fertility and rainfall is high. The gross margin analysis of these pathways over a 10-year period for a range of conditions typical of the region (Figure 2) demonstrated that there was little difference in the net profitability of the two main pathways unless higher stocking rates were possible – which applies in the higher rainfall, higher fertility areas of the region.

However, if the 'typical' (more common) scenario was considered (Figure 1) the economics of resowing pastures were worse than the 'ideal' and not much different to 'managed' as lower mean stocking rates apply (Figure 2). This leads to the general conclusion that the more appropriate pathways for development and improved environmental outcomes (as there was less disturbance to systems, less erosion risk and many native species remain) arise from conservative grazing management designed to retain the useful natural perennial species that are often lost rather than using reseeding to increase perenniality (Dowling *et al.* 2001). The 'managed' scenario involves less capital outlays and lower risks. Farmers are adopting that strategy. Within the 5 million ha of the region relevant to the analysis presented here, less than 0.01 of the area is being resown in any one year. The key point is that focus needs to be on net farm profits over the long-term rather than biological output or gross income. Much of the literature seems to ignore these criteria. A similar outcome is evident in the hill country of the United Kingdom, where many areas are no longer being resown and sown pastures are restricted to the more productive parts of the landscape.

Exceptions to these generalizations do occur, such as the intensively grazed perennial ryegrass, white clover pastures of New Zealand, which do appear to survive a high level of utilization at least for part of the year, without any need to resow. For example, pastures producing 15 t dry matter/ha/yr carrying 25 dry sheep equivalent (DSE)/ha, have an annual utilization rate of *c.* 0.6.

A shift in mindset: revisiting concepts for productive versus sustainable grassland systems

There are two general views of farming systems conceptualized as 'productivism' and 'post-productivism' (Wilson 2001). The productivism view is that of a 'factory' where resources are put in one end of a pipe and products extracted at the other with increased production and short-term profitability used as the yardsticks of success (Kemp *et al.* 2002). In the 19th century, J. von Liebig developed the concept of the 'law of the minimum', arguing that one factor is usually limiting production at any one point in space and/or time. Scientists have often focused on this approach and developed intensive farming methods and biochemical inputs to overcome production constraints (Ilbery & Bowler 1998). Society strongly supported this approach to 'feed the world', particularly through harsh times of food security, but now in times of plenty has become overly critical and rejects any sense of community responsibility. In this mindset the focus is restricted to a limited number of components with some consideration of efficiencies, but no solutions for unplanned or adverse environmental effects as these are considered externalities not necessarily to be managed within agricultural systems (Weiner 2003). Often in the search for higher productivity, limiting factors are applied to excess and any 'leakage' is seen only as inefficiency in primary production. High nitrate in water supplies is a legacy of this productivism approach. Nevertheless, von Liebig's 'law' helped sustain the 'factory' view up until the 1980s, when there was a change in focus from agriculture as 'production' to agriculture as 'ecosystem manipulation' (Weiner 2003), a conceptual shift required to accommodate increasing demands by society for more sustainable agriculture, including grazing systems for grasslands. The problem with the factory model is that while the view of production in terms of inputs and outputs is dynamic, its view of externalities such as nitrogen or glyphosate in runoff is static; hence the model is not very good at addressing these factors (Weiner 2003).

The related concept of 'grasslands as crops', developed from the early work of Stapledon and co-workers in Wales, proved an excellent stimulus to better management of grasslands, but is it still useful for addressing the problems facing us in the 21st century? The crop analogy has merit for good husbandry, but as most crops aim to be monocultures it conflicts with the reality of many grasslands where multi-species arrays need to be studied and managed at the community to ecosystem levels. Although nitrogen fertilized perennial grass systems are still important in many regions, systems that incorporate legumes to deliver better environmental outcomes are now used in the grassland phase to restore soil resources to crop systems. If grasslands are treated simply as crops, this may encourage over-use of resources and poorer environmental outcomes (Scholefield *et al.* 1993; Farruggia *et al.* 2004).

A second view of farming systems (coming more from managing natural grasslands) is an ecosystem model where it is acknowledged that the system is sustained by maintaining species and the cycling of water, nutrient and energy flows (Kemp *et al.* 2001, 2002; Weiner 2003). In this 'systems' scenario, it is acknowledged that the products harvested from grassland ecosystems are significantly less than the internal flows of energy and nutrients, and that the ecosystem processes need to be maintained in order to sustain production. Because more of the factors affecting production (including many environmental factors) are considered to be part of a system, the ecosystem view aims to cycle nutrients internally and minimize the leakage, as much as possible, of more judiciously applied inputs. A focus on overcoming single limiting factors is then inappropriate because the farm as a managed ecosystem is not self-delimiting (Weiner 2003). This approach fosters a more conservative, optimizing net profit strategy. Examples of shifts towards 'best' practice that emphasize environmentally friendly forms of production are already evident in new sustainable management practices implemented by farmer self-help groups such as Landcare Australia (Campbell 1994).

A switch from a 'factory' to 'ecosystem' view of farming has implications in how we develop management strategies for grassland systems and evaluate their impact. A key consideration is that within an ecosystem it would be impractical to manage each component to an optimum. Rather, there are a range of values around the optimum that do not result in great losses in productivity or ecosystem function; hence managing within a range is acceptable, e.g. animal gain/ha (Kemp 1991). Farmers can manage more successfully over a range than continually chasing optimum or maximum values, thus corrective actions only need to be initiated when near the limit of that range, rather than continuously. This goal of maximum sustainable yield by using an optimal range which maximizes long-term profit or economic survival (as may be the case in developing countries where farmers live close to subsistence) illustrates that the ecological view forces us to define our objective on a different time scale than the factory approach which is typically short-term (Weiner 2003).

Linkages between the environment and grassland production

The real difficulty of the ecosystem view is assigning value to the production and environmental components of the grassland system, which are often measured in different and non-interchangeable currencies. Weiner (2003) asks, for example, how much money would compensate a community for groundwater polluted by nitrate? Or how much is a rare species worth? Understanding the linkages between grazing, productivity and environmental changes is paramount for grassland management where contrasting perspectives of economics and public concerns are emphasized.

While some of the close natural linkages between grazing, grassland productivity and gross environmental effects are well known (e.g. normal seasonal cycles, the extremes of droughts and floods; Retzer 2006), some more subtle effects and how the resource base is sustained are ill-defined. Grazing can affect the soil water balance, depending upon the grazing intensity (Smoliak *et al.* 1972; Naeth & Chanasyk 1995), the residual herbage mass (Hughes *et al.* 2006) and the proportion of bare ground (Naeth *et al.* 1991). Reductions in soil water through grazing are attributed to soil compaction and sealing by animal treading, which increases surface runoff and leads to increased nutrient losses and reduced infiltration rates (Elliott & Carlson 2004). These grazing impacts on grasslands can be modified by management with more conservative utilization strategies (e.g. maybe 0.25 below biological optima), effectively increasing the perennial grass composition, which in turn reduces runoff, increases water transpired (reducing salinity and acidity risks) and reduces the need to reseed to restore ground cover (Michalk *et al.* 2003*b*). These components may have been influenced more by the standing herbage mass than directly by grassland growth rates or livestock productivity. The challenge for farmers is to determine the grazing pressure where adverse environmental impacts are low, yet productivity is satisfactory (Figure 1) These interactions will be considered from an ecosystem perspective in terms of the management of water, nutrient and energy flows, and the diversity of species required to sustain the ecosystem function.

Managing water with grasslands

Sustaining clean and safe drinking water and irrigation supplies to meet the needs of the global population is a major issue for the 21st century. Water demand already exceeds supply in more than 80 countries which together account for 0.4 of the world's population (Swain 2001). In Africa alone, more than 300 million people live under severe water restrictions (Bennett 2000). Grasslands are vitally important for the provision of water for agriculture, industry and domestic use.

The way grasslands are managed can have major impacts on the water cycle, ecosystem function and biomass production. In Australia, solutions to these problems lie in increasing the longevity of plants in the landscape (Singh *et al.* 2003). Perennial-dominated grasslands fulfil two roles in water management – they efficiently utilize soil water, due to deeper root systems and longer growing seasons than annual species, and they can protect the soil surface from soil and nutrient loss, particularly during high intensity short-duration storms. Unfortunately there is often a decline in the perennial component in grasslands, resulting in more variable production over time, higher incidence of weed invasions, soil acidification, acute soil erosion and increasing salinity. This decline arguably reflects grazing pressures that are not sustainable.

Harvesting water

Clean runoff and aquifer recharge from grassland catchments is crucial to maintaining water supplies for agricultural, industrial, domestic and environmental use, food security and to progress many societies beyond subsistence (van Wesemael *et al.* 1998; Raju 1998). In addition, groundwater supports major ecosystems by providing baseflow to rivers and perennial flow to wetlands of international wildlife importance. Grassland management practices can vary the proportion of surface runoff to aquifer recharge (Bergkamp 1998). This was evidenced in the recent Australian drought, where over-grazing was controlled and less water (from the limited rain that did fall) flowed into dams and rivers. Maintaining herbage mass > 2 t DM/ha in upland, recharge areas (Figure 3) effectively controls runoff (Packer *et al.* 2003). Excessive clearing and high grazing pressures results in less water being retained in the landscape, higher runoff in average to wetter seasons, reduced soil water recharge and reduced dry season river flows.

Changes in vegetation structure can have differential impacts on water management. On the Edwards Plateau in Texas, for example, woody weed (mainly *Juniperus*, *Quercus* and *Prosopsis* spp.) invasion of savanna grassland, due to reduced fire frequency and overgrazing (Scholes & Archer 1997), has reduced recharge to the Edwards Aquifer because of the higher evapotranspiration losses from shrub cover (interception and transpiration of woody vegetation is higher, e.g. > 0.70 of precipitation for juniper (Eddleman 1983) compared with < 0.18 for herbaceous vegetation (Thurow *et al.* 1987)). Wu & Tiessen (2002) estimated that the hydrological impact of a shrub cover of *c.* 0.2 would decrease water yield to the aquifer by 35 %. Invasion of Australian *Acacia* spp. in South Africa (Dye & Jarmain 2004) had a similar negative impact on aquifer recharge, as have reafforestation projects. Restoration of forest cover in Spain (Bellot *et al.* 2001) and India (Sikka *et al.* 2003) reduced both runoff, by *c.* 25 %, and aquifer recharge, by *c.* 40 %.

In environments where grasslands have been a significant part of ecosystems, learning to manage them appropriately would be preferable to altering the ecosystem. Recharging aquifers can be advantageous for human health as there is a reduced risk of pathogens such as *Cryptosporidium* and *Giardia* that often contaminate surface waters (David & Mazumder 2003). As a minimum, domestic water supplies need to come from water collected from catchments with high grass cover. A high quality natural habitat can significantly improve water quality and filtration costs (Sutherland 2002).

Dryland salinity and soil acidification

Australia has the reputation of being the world's driest inhabited continent, yet salinity caused by excess water in the wrong parts of the landscape is a major problem in both irrigated and dryland agriculture. Up to 17 million ha of Australia's more valuable crop and grassland is at risk of salinisation by 2050 (National Land and Water Resources Audit 2001). Induced salinity has been known since land clearing, agriculture and irrigation developed, affecting environmental values in many other countries including the United States, Canada, Thailand and Pakistan (Salama *et al.* 1999*a*, *b*; Mahmood *et al.* 2001).

Accelerated soil acidification is recognized as a major degradation issue that affects the sustainability of current production systems in both temperate (Ridley *et al.* 2004) and tropical (Noble *et al.* 1998) environments. Developing acidity under grasslands has long been recognized in Europe where lime is regularly applied, in tropical America where more than 800 million hectares are classified as having acid soils and in southern Australia where some 24 million ha have a pH < 4.8 (Cregan & Scott 1999). Some soils are naturally acidic but other grassland soils become acidic as a result of land use change and/or inappropriate management. Short-term annual pasture legume leys are now recognized as a significant cause of acidity in Australia (Ridley *et al.* 2000, Noble *et al.* 2002). The symptoms caused by toxic levels of aluminium (Scott *et al.* 2000) are less visible than those that occur with erosion and salinity and the gradual decline in production is often ascribed to other factors such as seasonal conditions.

How have these problems arisen? In general, salinity and acidity result from a substantial change in land use practice that has altered the hydrological balance from catchment to regional scales. Salinity tends to be worse in regions where the rise in water table levels carry mobilized soil salts to the surface in susceptible down slope floodplains, causing die-back of native trees (Slavich *et al.* 1999), and eventually salt scalds appear (Poole *et al.* 2002). This is the result of excessive clearing of the woodlands in the recharge areas and their reversion to volunteer grasslands and sown pastures for livestock grazing. The salinity problems that emerge over a relatively short time-frame is both a farm and community problem as its effects are evident not only in a decrease in farm productivity, but in damaged infrastructure (e.g. roads and buildings) and poor water quality in major river systems. Excessive nitrate from legume-dominant swards and livestock urine patches, coupled with excess drainage resulting in nitrate leaching, all contribute to soil acidification. Management of salinity and acidity requires control over the partitioning of the water balance and the depth of water tables. Pressures to extract increasing returns from livestock caused by declining terms of trade in Australia has led to high grazing pressures and significant deterioration in the perennial species base – commonly to less than 0.2 composition, which exacerbates these problems (Moore 1970; Kemp & Dowling 1991; Kemp & Michalk 1993). Similar problems occur throughout the world.

The risks of acidification and of salinity in grasslands can be reduced by encouraging the growth of perennial plants to use more water and capture nutrients throughout the growing season (Ridley *et al.* 2000; Noble *et al.* 2002). Management practices to increase/maintain the proportion of perennial species (perenniality) of grasslands are being developed (Kemp *et al.* 2000; Michalk *et al.* 2003*b*). Both perennial grasses and strategically placed trees and shrubs (if they cover 0.16–0.22 of the catchment) have a role (White *et al.* 2002). The aim is to manage recharge or discharge to levels similar to natural ecosystems (Hatton & Nulsen 1999) as engineering solutions are too expensive for many types of grassland (Mahmood *et al.* 2001). A further strategy is to identify plant species that are productive and help maintain ecosystems under saline (Cocks 2001) and acid soil conditions (Scott *et al.* 2000). In central New South Wales, Australia, deep drainage was reduced in the order: native C3 grasses < sown C3 grasses < mixed C3/C4 grasses, when present at the same level of herbage mass (Hughes *et al.* 2006). Increasing the area of grassland dominated by perennial herbage plants reduces the need for trees (Dunin 2002). Studies of Mediterranean systems (Joffre & Rambal 1993) have determined the optimal proportions of perennial grasslands and trees needed to manage the water balance and to capture nitrate. The wider use of lime for acid soil management is restricted to higher rainfall, more fertile and profitable soils.

Economics of water management on grasslands

For most farmers, management of grasslands to alleviate water, salinity and acidity problems is only of secondary concern, compared to obtaining an economic return from livestock production (Pannell 1999). Adoption of management practices that promote safe runoff, enhance aquifer recharge or reduce salinity through reduced drainage will depend on how producers are rewarded for the improved off-site water yields or reduced salinity that benefits the community at large. On the Edwards Plateau, for example, the value of grasslands for livestock production decreased as woody cover increased, but ranchers tolerated brush encroachment up to 0.30 cover because of the high cost of woody weed control and the benefits accrued to alternative land uses such as deer hunting and aesthetics (Thurow *et al.* 2000). Olenick *et al.* (2004) calculated the opportunity cost of additional water ranged from $US 260 to $440 per ha when rangeland was cleared to < 0.03 brush cover, a level that maximized water yield potential. Few ranchers are likely to control and maintain brush to 0.03 density without publicly funded cost-sharing which has strong community support; central Texas is facing water shortages (Thurow *et al.* 2001).

Therefore, the proportion of a farm that is sown to perennial plants or treated to control woody weeds is more an economic than an environmental decision. However, Australian work has found that the level of use of perennials promoted through traditional education and extension is less than that required to halt expansion in saline areas (Bathgate & Pannell 2002). Achieving a better environmental outcome will depend upon farmers receiving prices for their products that reflect the environmental services delivered, such as clean water, or from direct subsidies.

Managing nutrient loss in grasslands

Intensive grassland production

This has come to rely on the identification and alleviation of mineral deficiencies that limit plant growth. Fertilizer application, particularly nitrogen, has significantly increased productivity of intensively managed tropical (Martha *et al.* 2004) and temperate grassland systems (ten Berge *et al.* 2002). However, the environmental effects of eutrophication of surface and ground water due to nutrient leakage are now evident at regional and global scales (Oenema *et al.* 2003). Nutrients in animal faeces and urine can be utilized for growing plants but are also serious sources of pollution (ten Berge *et al.* 2002) and greenhouse gas emissions (Chadwick *et al.* 2000). As previously argued, application of the 'law of the minimum' is not appropriate within a sustainability management framework. There is a need to balance these conflicting goals of profitable production and environmental protection, particularly in the management of both inorganic and organic fertilizers. The main challenge is to achieve better control of nutrient leakage beyond farm boundaries; though within a farm some nutrient movement can be accommodated.

Nitrate leakage is a major issue (McGechan & Topp 2004; Rimski-Korsakov *et al.* 2004) and it is important to improve the nitrogen (N) efficiency of grassland farming (Eriksen *et al.* 2004), especially intensive dairy production where N use efficiencies are low (Jarvis & Aarts 2000). Nitrogen levels of 400–600 kg/ha/yr, applied to tropical (Martha *et al.* 2004) and temperate (ten Berge *et al.* 2002) grass pastures have efficiencies of 40–70 kg DM/kg of applied N. Leaching losses from grasslands are generally low compared to cropping systems, but can exceed 34 kg N/ha/yr, the limit set by the EU Nitrates Directive to maintain groundwater nitrate concentration below 50 mg/l. In Belgium, laws limit residual 'post-harvest' soil nitrate-N to < 90 kg N/ha in the soil profile (0–0.9 m) between 1 October to 15 November (Nevens & Rehuel 2003). In the Netherlands, farmers have to maintain records of nutrient use and are taxed on nutrient surpluses generated from their farms, with penalties up to €400/ha for livestock producers (Ondersteijn *et al.* 2002). Excessive nutrient runoff can also have regional or national consequences. Nutrient runoff from the central United States, for example, has changed the ecology of areas surrounding the mouth of the Mississippi and led to a hypoxia problem in the Gulf of Mexico (Rabalais *et al.* 1991).

Despite these impacts and penalties, farmers are reluctant to comply with regulations to reduce nutrient inputs because of the decline in livestock performance that results when N applications to cut or grazed grasslands are reduced (Valk *et al.* 2000). An analysis of fertilizer strategies in Europe suggested that focussing on efficiency provides the best means to reduce leaching losses and minimize off-site impacts (Ondersteijn *et al.* 2002). Since only 0.30–0.50 of applied N and *c.* 0.45 of applied P is typically taken up by target plants (Smil 1999, 2000), improved nutrient-use efficiency can be achieved. Applying fertilizer during periods of peak plant demand, placing fertilizer nearer plant roots and using smaller, more frequent applications all have the potential to reduce nutrient losses while maintaining yield and quality (Tilman *et al.* 2002). All this requires actively growing plants with well-developed root and shoot systems, typically perennial species, not heavily grazed plants that are struggling to survive.

Integrated landscape management can complement paddock management to effectively control nutrient fluxes and leakage within catchments either in surface runoff or ground water discharged as base flow (Schilling & Wolter 2001). Extensively managed grasslands could prove crucial in catchment management to effectively lock up nutrients trapped from adjacent areas of intensively fertilized crops and pastures. Buffer strips comprising 5 m of grassland and a line of trees may effectively trap N in soil water flows (Borin & Bigon 2002). Changes in species composition can improve nutrient interception (Myklestad 2004). While new management approaches provide potential solutions to many nutrient problems, it is clear that for intensively managed grassland such shifts are mandatory in both developed and developing nations.

Extensively managed grasslands

These areas depend on nutrients released from parent material and organic matter by biological and chemical processes. Since these grasslands rarely receive fertilizer, legumes often play a key role in productivity through the supply of biologically fixed N and their nutritional value. Nutrient release from stored organic pools depends on litter quality, environmental conditions and the level of microbial activity (Swift *et al.* 1979); subsequently these nutrients need to be captured by desirable perennial grasses. Changes in species composition can significantly affect the dynamics of nutrient cycling. Less palatable plant species tend to lock up nutrients and reduce grassland productivity (Moretto & Distal 2003). Grasses with a high C:N ratio immobilize nutrients due to slow decomposition rates (Hobbie 1992) and thereby limit opportunities for palatable species with higher nutrient requirements to re-establish (Moretto & Distel 2003).

Increasing the legume content of grasslands is likely to occur, as the impacts of global warming are projected to increase legume yields relative to grass making them potentially more profitable to grow, especially in high latitude areas of the northern hemisphere (Frame *et al.* 1998). Doyle & Topp (2002) estimated that the European livestock farming industry could gain an annual benefit exceeding €1300 million by growing and harvesting pure legume and grass-legume mixtures in place of the current grass silage pastures. This is already the case in temperate Australia, where *Trifolium subterraneum* combined with modest applications of superphosphate underpin the extensive livestock production systems, although often the proportion of clover is below that required for optimal animal production (Wilson & Simpson 1994). Oversown legumes (particularly from the *Stylosanthes* genus) are used to augment the production and quality from tropical rangelands as part of improvement programmes used to increase beef output per hectare (Thomas & Sumberg 1995; Miller *et al.* 1997; Michalk 2004).

There are large amounts of soil N and P that are unavailable to plants and developing management strategies to release more of these 'fixed' nutrient pools is an obvious area for research. Better nutrient management would require sequestration of mineral nutrients within more readily available organic pools, the retention of those pools in the system and then the managed release and capture of nutrients by desirable plant species. In practice, this may involve using grazing tactics to maintain litter and retain higher quality plant species with active root systems to minimize nutrient loss. Overgrazing is arguably the biggest single cause of nutrient loss in extensive grasslands. Wind erosion and nutrient loss in Chinese grasslands can be clearly linked to adverse grazing practices (Dong *et al.* 2000; Michalk *et al.* 2003*a*) and managing species composition is crucial for reducing nutrient losses. In central Asian grasslands, wind erosion is most pronounced during the period from late March through to late May, when re-sprouting C3 perennial grasses (*Stipa baicalensis*, *Aneuropidium chinense*) establish ground cover to stabilize that soil surface (Li *et al.* 2004). However, overgrazing in spring by livestock emerging from the protracted winter in poor condition causes a shift in composition from C3 to C4 (*Cleistogenes* spp.) grasses, which initiate growth at higher temperatures that coincide with more favourable soil moisture regimes (Michalk *et al.* 2003*b*). The loss of the C3 species leaves the soil surface exposed in the period of strong winds.

Managing carbon in grasslands

The energy in organic carbon compounds within grasslands is central to their productivity and environmental values. Estimates suggest that grasslands account for > 0.1 of the total biosphere C store (Jones & Donnelly 2004), > 0.9 of which is sequestered below ground (Schuman *et al.* 1999). As atmospheric CO_2 concentrations increase, identifying opportunities and promoting practices that enhance C stocks is a major grassland management objective. This is a formidable challenge because grasslands are complex ecosystems subjected to a wide range of environmental and management conditions. Nevertheless, under existing management conditions most temperate grasslands are considered to be C sinks (Jones & Donnelly 2004), although their potential to sequester C is determined by their productivity. In the moderately productive Central Plains of the United States, for example, Gebhart *et al.* (1994) measured C accumulation of 1.1 t C/ha/yr, whereas in the more arid shortgrass prairie of Colorado Burke *et al.* (1995) measured accumulation of only 0.03 t C/ha/yr. Further, the same grassland may sequester C at different rates depending on its condition, with high rates sequestered during the 'restoration' phase relative to grasslands in a 'maintenance' phase (Schlesinger 1990; Fisher *et al.* 1994).

The amount of soil organic matter retained by grassland soils is strongly influenced by management (Conant *et al.* 2001). Land use change, especially the conversion of large areas of grassland to crop production (Vitousek *et al.* 1997; Scholes & Noble 2001) has contributed significantly to elevated atmospheric CO_2 levels. Estimates suggest that the combination of deforestation, grassland conversion and land management practices accounts for about 0.25 of C released from soil organic matter. Cultivation of the grassland steppe in China, for example, decreased soil organic carbon by 25 % in 8 years, rendering the soils highly susceptible to erosion (Wu & Tiessen 2002). The challenge for grassland management is to reverse CO_2 losses by storing more C in plant and soil organic matter to help minimize adverse environmental impacts (Vleeshouwers & Verhagen 2002), as well as to aid water and nutrient management. Farming systems where pasture phases are wedged between cropping cycles pose a continuing problem to accumulation of C.

In general, those permanent grasslands most depleted by poor management have the greatest potential for soil C increase (Jones & Donnelly 2004) through the application of management practices such as moderate fertilizer application, oversowing legumes and moderate stocking density that increase forage production (Conant *et al.* 2001; Reeder & Schuman 2002). These practices not only increase biomass, but replace annual species which lack the dense fibrous root systems conducive to soil organic matter formation and accumulation with deep rooted perennial species with higher carbon sequestration capacity (Jones & Donnelly 2004). Soil C response to changed grazing management is less certain, particularly in the long-term, with both light-to-moderate (LeCain *et al.* 2002; Reeder & Schuman 2002; Wright *et al.* 2004) and heavy grazing (Schuman *et al.* 1999) increasing soil C, depending on grassland type and condition.

Carbon mitigation options from ruminant livestock include: increasing production per animal, modifying diet, improving management of bedding materials and manure heaps and reducing overall livestock numbers (Monteny *et al.* 2006). Of these mitigation strategies, only a reduction in the number of animals can be currently registered as a reduction in the Intergovernmental Panel on Climate Change inventory (IPCC 1997). These management options may involve important tradeoffs such as a change from intensive livestock production reliant on annual fodder and cereal crops to grass-fed systems in order to reduce greenhouse gas emissions (e.g. CH_4) and increase soil organic matter (Soussana *et al.* 2004).

Selecting livestock for reduced CH_4 emissions may provide further long-term solutions (Lassey *et al.* 1997) if it can be demonstrated that individual variation is under genetic control (Pinares-Patino *et al.* 2003).

Grasslands are not part of the current Kyoto accounting protocol (2007–2012) but the size of world's grassland resource makes it imperative to take into account this potential sink. Developing payments for carbon sequestration in grassland ecosystems could mean the difference between profit and loss for many livestock systems. However, this will require a commercially realistic verification system to be developed and accepted. Grasslands not only capture and store energy, but are often significant consumers of energy and from an environmental perspective these terms need to show a positive balance. However, it is clear that the energy balance becomes more negative as livestock production is intensified and manufactured inputs increase, especially N fertilizer (Kelm *et al.* 2004) herbicides and fossil fuels. This can be offset to some extent by the use of legumes and better management of farm manure. Ultimately, accounting procedures will need to consider the net energy balance if society is to make effective judgements about the sustainability of grassland practices.

Managing biodiversity

Intensified land use in agriculture and forestry, urbanization and climate change are recognized as the main causes of biodiversity loss (Tscharntke *et al.* 2005). However, the long-term sustainability of grassland ecosystems and the services they generate depends on conserving biodiversity at a landscape scale to ensure recovery from minor and major, small- and large-scale disturbances (Bengtsson *et al.* 2003). Conservation biologists have been mainly concerned with the origins and maintenance of biodiversity, whereas agroecologists have been mainly concerned with its effects on ecosystem function and how these effects can be better managed in a production context (Vandermeer & Perfecto 1997). There is considerable debate about how agriculture and biodiversity can be managed alongside each other (Firbank 2005).

Biodiversity and production

Biodiversity is crucial to the productivity of grasslands, with more diverse communities being more productive because they make full use of the most limiting resources (Zhou *et al.* 2006); however an understanding of the numbers and types of species that optimize production is still to be determined. Many agronomists assume that grass plus clover equals a good pasture. This reflects the 'factory' approach where management is focused on a few species and their specific requirements, yet the potential value of many other plant species are ignored (Robertson & Swinton 2005). Early work in the new field of biodiversity studies, using small plots, suggested that maximum productivity occurred when 6–10 plant species were present (Tilman 1996). At a small scale, sometimes fewer species were sufficient to maximize grassland production (Nicholas *et al.* 1997). Recent work in small paddocks (< 2 ha) in temperate Australia suggested that 10–20 species may be optimal for productivity (Kemp *et al.* 2003). The net primary productivity of those paddocks declined as species number increased from 20–50 (Figure 4) while the variability in net primary production through the year increased substantially (Fig. 5).

Bullock *et al.* (2001) showed hay yield to be higher (by up to 60 %) in species-rich meadows (25–41 species) than species-poor meadows (6–17 species), but the yield of species-rich meadows was < 60 % of intensively fertilized grasslands. Arguably, the significance of biodiversity in grasslands may appear only at the landscape scale as the optimum number of species would be expected to increase as the area and number of different resource niches increase (Bengtsson *et al.* 2002).

Since not all plant species are equal in their impact on the structure and function of plant communities, using plant functional type may provide a better definition of the relationships between diversity and productivity (Paruelo & Lauenroth 1996). The perennial grasses that dominate many grasslands (Tilman 1996) are often considered to be the main functional type driving ecosystem function (Kemp & Dowling 2000). However, if the fertility is low they may be less competitive and minor species such as annual grasses and forbs become more frequent (Kemp *et al.* 2003); which may alter soil water dynamics (Hughes *et al.* 2006) leading to dryland salinity and poor downstream water quality. The importance of plant functional type over species *per se* supports the species redundancy theory. *Lolium perenne*, for example, can be replaced by *Festuca arundinacea* (tall fescue) without any significant impact on grassland productivity, whereas the replacement of a perennial grass with a range of forbs or annual grasses may significantly alter productivity and ecosystem function. An implication for native grasslands is that management to conserve minor species that are part of a common plant functional type may not be important for productivity as natural grasslands are unlikely to be dominated by one or two species.

Invariably other species invade under heavy grazing and variable climatic conditions, supporting the view that stable grasslands require many species.

Weed invasions, particularly by forbs, is perceived by many as the biggest issue confronting grassland managers. However, in more simple sown grassland the typical mixtures of grass and clover can be augmented with other forbs as 'gap fillers'. The release of cultivars of *Cichorium intybus* (chicory) (Rumball 1986) and *Plantago lanceolata* (plantain) are a revival of an old practice (Foster 1988) that fell out of favour during the 20th century. More diverse sown grasslands can reduce invasion of other species (van Ruijven *et al.* 2003). Managing grasslands to enable existing species to utilize more resources to maintain higher mean levels of herbage mass can also restrict weed invasion (Badgery 2003; Meiners *et al.* 2004).

Livestock practices such as the timing and intensity of grazing are powerful management tools that affect both plant species composition and richness of grasslands (McIntyre *et al.* 2003). Developing the pivotal strategies that maintain profitable livestock production enterprises and at the same time enhance local and regional biodiversity is a major challenge for farmers, land management agents and conservationists (Watkinson & Ormerod 2001). Unfortunately, we still have only a very basic understanding of how to manage the impacts of different management practices on biodiversity (Dorrough *et al.* 2004), despite considerable research to tease out the linkages between biodiversity, productivity and ecosystem services (Naeem & Wright 2003) and that this point was being acknowledged by Stapledon 80 years ago (Stapledon 1927). These impacts extend beyond the edible herbaceous strata, as studies on invertebrate communities in grazing systems indicate that more intensively managed grasslands often have lower invertebrate richness and abundance (Di Giulo *et al.* 2001).

Nature conservation

Ecologists and conservationists have often focused on saving the last remnants of pristine ecosystems (Tscharntke *et al.* 2005). However, this focus is shifting as there is greater recognition that grazing practices with reduced grazing pressures usually retain species, which provides a valid means to conserve the multifunctionality of disturbed grasslands. Grassland uses range from commercial livestock production to wildlife tourism. To attain production and biodiversity goals, the amount of forage utilized needs to satisfy the needs of all relevant herbivores, and enable all the desirable species present (including native species) to persist over the long term.

In grasslands that have been utilized for production, it is reasonable to assume that any rare and endangered species have either been lost long ago, or if still present are being maintained under current management practices. Experience in Australia has been that grassland areas that become part of the National Park system need to be grazed to prevent invasion by unwanted species that threaten the grassland (Lunt 2003). For grasslands across southern Australia (Kemp *et al.* 2003), native plant species in mixed grasslands are maintained where the average herbage mass did not decrease below 2 t DM/ha. This provided farmers with a simple management guideline to conserve those species.

Management for wildlife is becoming an increasingly important economic activity. For example, 'Ducks Unlimited' in North America is funding habitats (there are 50 million bird watchers in the USA and Canada) while South Africa now has 45 000 private game reserves. Problems can arise where a single species becomes the sole focus for management, which can have adverse consequences for the rest of the ecosystem. Limited culling of animals and resultant over-grazing so that tourists can more readily see wildlife is an increasing problem.

The biggest threats to species conservation are changing land use. Many grasslands are now dominated by non-preferred species and/or invaders from other environments. To restore rare and endangered species in these circumstances can be an expensive task that may require transplanting individual grass plants (Hocking 1998). Little work has been done on the restoration of rare plant species in grasslands. Some disturbance of the ecosystem is required to enable any plant to establish. Knowledge of the size of suitable micro-sites can be used to help design suitable management practices (Bullock *et al.* 1995). Gap sizes can be varied with grazing tactics. Ecological theory suggests that species richness is maximized at intermediate levels of disturbance (Huston 1979). The pathway to restoration can be quite different to that of degradation as identified in the concepts of 'state and transition' (Westoby *et al.* 1989).

An increasing area of interest is the maintenance of meso- and micro-fauna within grasslands, in part because of their critical roles in cycling nutrients and energy. In a study on a range of grassland systems in central NSW, Australia, the majority of soil insect species were retained across a range of grassland systems, but the proportions changed (Reid 2004). In Wales, retaining a higher average herbage mass in summer resulted in more *Coleoptera* (beetle) species within the grassland, especially those dominated by native plant species (Dennis *et al.* 2004). It was considered that these effects were constrained by the previous history of the grassland, e.g. drainage, fertilizer and lime inputs and botanical composition. Studies on invertebrate communities in grazing systems suggest, however, that more intensively managed grazing systems have lower invertebrate richness and abundance than ungrazed or conservatively grazed grasslands (King & Hutchinson 1983). High fertilizer inputs can lead to species-poor swards, even years after fertilizer applications cease, which may be the cause of some of the effects noted (Walker *et al.* 2004).

Biodiversity management – paddock to landscape

Intensifying use which simplifies grasslands affects biodiversity at both the paddock and landscape scales, due to extinction of small, fragmented populations (Tscharntke *et al.* 2005). Different strategies for managing biodiversity need to be formulated that take into account the spatial scales of the paddock, property and landscape (Firbank 2005). Landscape is particularly important because the long-term sustainability of ecosystem services depends on conservation of biodiversity at this larger scale. Management that retains a mosaic of well-connected habitats in different successional states is most likely to maintain high biodiversity with capacity to recover from disturbances (Bengtsson *et al.* 2003). This approach is already a common practice, reflected to some extent in EU policies for grassland restoration and management (Smith *et al.* 2003). A mosaic of different fields connected by non-cropped habitat is known to increase diversity of breeding birds, ground beetles, spiders and butterflies (Benton *et al.* 2003). Using a mosaic approach enables species to move between sites to avoid creating islands that limit the viability of populations (Poschlod *et al.* 1998).

The advantage of a landscape focus for biodiversity is that while the diversity of paddock, farm or grazing area is a function of landscape diversity, it only constitutes a proportion of landscape richness as local communities are mostly unsaturated. This means that since paddocks do not have all the necessary species present to realize the potential ecosystem functions (Bengtsson *et al.* 2002), grazing practices at the local level should be such that species migrations are encouraged as a major component of sustainable grassland management. Such management is more important in simple grassland landscapes than in complex landscapes, where the complexity may compensate for biodiversity loss due to management at smaller land units (Tscharntke *et al.* 2005).

Delivering multifunctional grassland landscapes will require close collaboration between landholders (Firbank 2005). Equally, there is great scope to use modelling techniques to identify and evaluate multi-goal grassland management at the landscape scale and hopefully improve the consistency of signals that are accepted by all stakeholders as appropriate to promote sustainable development.

Bringing production and environmental goals together

The dilemma considered through the present paper is how to achieve production goals while attaining many of the environmental goals society now expects for grassland resources. The challenge is to develop a common framework that includes both production and environmental goals and from which guidelines can be provided for livestock producers. The main tool available to livestock producers is to vary stocking rates in relation to the feed requirements to optimize animal production (per head and per hectare), the available herbage mass and capture environmental benefits. As discussed earlier, many key environmental issues such as water and nutrient management are related to herbage mass and thus it provides an intermediary measure of the state of the system for both production and environmental criteria. A suitable framework is the relationships between stocking rate and animal production per head and per hectare (Figure 6) developed by Jones & Sandland (1974); for the purposes of the present discussion their normalized, linear function (for gain per head) is used. As pointed out by Connolly (1976), that underlying relationship may also be curvilinear (e.g. quadratic).

The on-farm variability in forage resources, spatially and temporarily, means that it is arguably impractical ever to maintain the system at the biological optimum for production per hectare, i.e. the maximum point on the curve in Fig. 6 for any extended period. A realistic goal would be to aim for 0.75 of that maximum, which is also probably closer to the economic optimum for many systems. As the biological maximum is approached, the gain from each extra animal tends to zero, while the costs of maintaining that animal remains above zero. Economic analyses of optimal stocking rates tend to show a decline in the sustainable stocking rate as those analyses extend from a single year to decades (Randall Jones, personal communication). This is a result in the inclusion of more maintenance costs, including resowing, destocking, etc., over longer periods of time.

There are two instances where producers can achieve the 0.75 goal, represented by points A and B in Fig. 6. In the past, many producers arguably sought to stock pastures towards point B, probably due to being over-optimistic about seasonal conditions, aiming for a high utilization level, maximizing stock numbers for social reasons and maybe not appreciating which side of the biological optimum they were on. However, at point B, compared with A, the stocking rate is nearly three times greater and the growth rate of animals only one-third; this has significant implications for production efficiency and environmental impacts. Net profit would clearly be higher at point A. To achieve the higher animal growth rates at A it is a reasonable assumption that the quantity and quality of the herbage available is at least 0.75 of that required for maximum animal growth rates (this applies for the linear function in Fig. 6, but if a quadratic function applied then the per head gain and hence forage available would be slightly larger – D. Kemp, unpublished). For sheep, this means 1.5 t (green) DM/ha, a level approaching high intake levels and at which water management is enhanced, biodiversity levels are reasonable and the desirable species are more likely to be maintained. The relative impacts of managing to points A or B are summarized in Table 1.

One of the major benefits gained from managing to A rather than B is a substantially greater profit. This qualitative rating identifies a host of reasons for managing to point A. The only uncertainty is forage quality, where the greater herbage mass that would result at A may have, e.g. a lower legume content and older leaf age. These ratings apply where the majority of the animals produce saleable products.

A further implication of these relationships (Fig. 6) for improving the sustainability of grazing systems, which appears to have been rarely exploited, is in estimating the reductions in stocking rates required in adverse seasons, e.g. droughts, or cold winters. During adverse seasons when forage supply is limited, animal production declines towards maintenance, which means that the relationships move to the far right of these curves, sometimes below the axis where weight loss occurs. To then return to somewhere closer to point A would require a 75 % reduction in animal numbers. Supplements could then be fed to animals to overcome such gross deficiencies, but to continue to maintain high stocking rates in such circumstances would result in a high grazing pressure and probably a loss in desirable plants. Overlaying such relationships with herbage mass, botanical composition and other performance measures that can inform on system sustainability would help resolve the boundaries within which livestock numbers should be managed.

CONCLUSIONS

A theme that is emerging, and one that could develop further, is a partial return to the initial activity of gatherers and hunters, i.e. thinking about the level of harvest from grassland ecosystems at which system function is sustained, rather than simply maximizing the utilization of the forage available, which in many environments results in the rapid degradation of those grasslands, necessitating their replacement with sown species or abandonment to the vagaries of nature in the hope that one day they will again be usable. The last point is now within a Chinese Government policy to 'forbid grazing' in highly degraded areas. In the Inner Mongolian Autonomous Region for example, some 70 million ha will be locked up over the first decade of the 21st century. Less well-developed is a policy as to how that land will be used after the initial period of forbidden grazing. The key concept underlying these impacts is the level of utilization of the available forage and how to estimate what is appropriate for any given system. In the past, an appropriate level of utilization was often the amount that could be harvested by livestock within a short period, sufficient to provide a short-term economic return on the forage sown. Today, suitable levels of utilization need to satisfy not only the production goals, but also the requirements to sustain the desired local environmental values, e.g. clean water, biodiversity, nil pollutants and maintenance of ecosystems.

It is difficult to set sustainable levels of forage/grassland utilization, as we know little of the levels that will support grassland ecosystem functions over the medium to long-term. In general, it is likely that utilization levels will depend upon the productivity of the environment (e.g. drier environments with low productivity probably require lower levels of utilization), the length of growing and non-growing seasons and how well plant species are adapted to the local environment (e.g. species near the edge of their range are arguably more susceptible to over-use).

With the majority of the world's grasslands considered to be degraded to some degree, how can the need to achieve the levels of food, fibre, fuel and medicine production required be satisfied, while enhancing the environment? Well-managed grasslands based upon improving the perenniality of the ecosystem should retain species and manage water, nutrient and energy cycles with reasonable efficiencies, and still achieve suitable levels of production. This can be assessed by monitoring species composition, the quality of water coming from the catchment and the efficiency of nutrient use over the medium to long-term. There is a requirement that these needs be translated into tools that farmers can use daily to track their progress and to know if their systems are sustainable. Evidence needs to be provided that recommended tactics and strategies are compatible with normal farm management and economically acceptable. The general animal production relationships discussed earlier provide some guidelines to help livestock producers locate their relative positions and adjust stocking rates accordingly, though those adjustments may not always be as much as society would desire.

Many societies now expect that agriculture will look after the environment. The 'polluter pays' principle, however, has not always been applied in agriculture, as many of the environmental values often reflect societal wants for enhancement, e.g. biodiversity, as opposed to outright pollution. The benefits from remedying environmental problems do not necessarily return to the farmer, they often return to the community at large, even across national boundaries. These effects mean that there is a good case for direct community payments to solve those environmental problems that are beyond the range wherein livestock producers can still make a satisfactory net profit, e.g. at relatively low stocking rates < 0.25 of the biological optimum. An alternative of extracting market premiums for good environmental practices has had only limited success and is difficult to apply universally to remedy general problems. A case exists for direct or market-based payments for environmental/ecological services, and many grasslands could be used for these purposes, e.g. storing carbon, delivering clean non-saline water, and maintaining biodiversity. Such payments need to be global in approach as many of the environmental problems of grasslands occur in the developing world.

The present paper distils the outcomes from many discussions over many years with colleagues involved in grassland research and development and in particular the many livestock producers who have keenly supported research programmes. We extend our thanks to them all and especially to the industry groups in Australia (Meat and Wool) that have funded this research. Funding from the International Grassland Congress and the Stapledon Trust provided further opportunities to develop these ideas.

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Table 1. *Comparison of managing grassland at points above and below the optimum to achieve 0.75 of the maximum productivity in animal gain per hectare (Fig 6). Approximate levels of various factors are rated, along with the relative advantage / disadvantage of managing to point A or point B. The more + symbols the greater the response; ? denotes uncertainty about response.*

Measure, relative to values at biologically optimal stocking rate	Point A	Point B	A / B
Animal gain/ha	0.75	0.75	1
Stocking rate	*c.* 0.50	*c.* 1.50	*c.* 0.33
Animal gain/head	*c.* 1.50	*c.* 0.50	*c.* 3.0
Time to reach market weights	*c.* 0.67	*c.* 2.00	*c.* 0.33
Implications			
Net profit	higher	lower	++
Management risk and uncertainty	less	more	++
Herbage mass/ha	high	low	++
Palatable grass content	high	low	++
Forage quality	lower	moderate	?
Weed risk	low	high	++
Biodiversity	stable	reduced	+
Soil erosion risk	lower	higher	++
Need to resow pastures	less	more	++
Water management	good	risky	++
Nutrient loss	low	high	++
Fertiliser need	low	high	++
Need for supplementary feed	low	high	++
Drought impact	less	more	++
Labour requirement	less	more	++

Fig. 1. Modelled patterns in stocking rates (DSE: dry sheep equivalents) for grasslands managed to a more productive state or (ideal or typical) resown for wool production. The alternative (typical) resown pattern is more common in the region. Estimates are for an average area in central NSW (D. R. Kemp, unpublished, using a gross margin model developed by Vere *et al.* 1993)

Fig. 2. Net present value of wool production for alternative grassland management strategies over a 10 year period (D. R. Kemp, unpublished data, using a gross margin model developed by Vere *et al.* 1993). The 'managed' grassland is stocked at 0.80 of the ideal sown as per Figure 1.

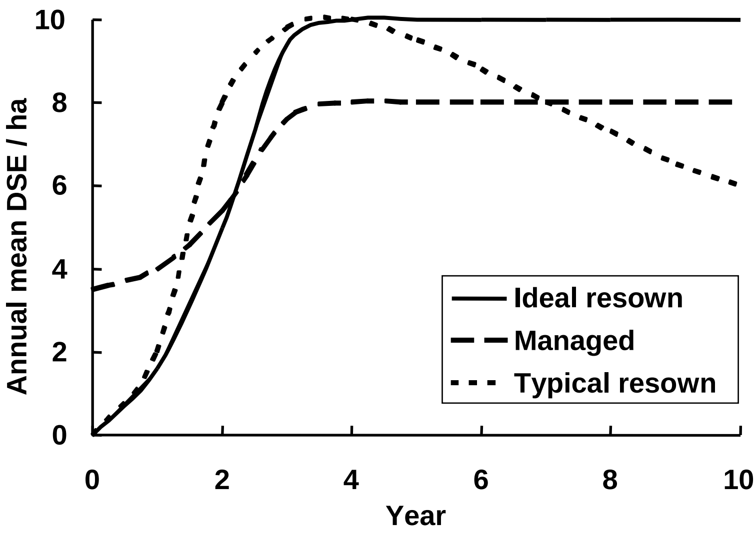
Fig. 3. Relationship between herbage mass for a range of pasture types (naturalized and sown) and maximum daily runoff. Data from Packer *et al.* (2003).

Fig. 4. Mean site annual productivity in relation to site total plant species diversity for seven grazing sites across southern Australia (Kemp *et al.* 2003).

Fig. 5. The relationship between species number and the coefficient of variability in seasonal production (from six weekly harvests over 3 years) for five grassland sites across southern Australia (Kemp *et al.* 2003).

Fig. 6. Relationships between relative stocking rate and relative animal production per head and per hectare based on Jones & Sandland (1974). Points A and B are where production per hectare is 0.75 of the biological optimum. The dashed line is $y = 2-x$ and the solid line $y = (2-x).x$

Fig. 1.



Annual mean DSE / ha
10
8
6
4
2
0
0
2
4
6
8
10
Year
Ideal resown
Managed
Typical resown

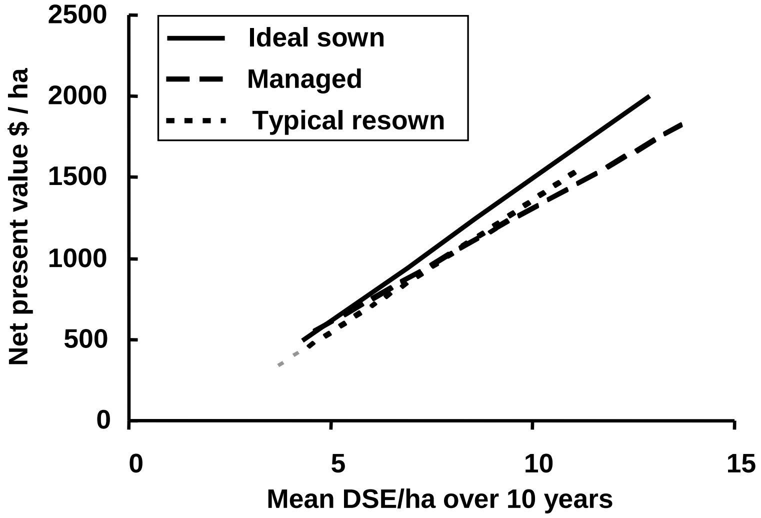

2500
2000
1500
1000
500
0
Net present value $ / ha
Ideal sown
Managed
Typical resown
0
5
10
15
Mean DSE/ha over 10 years

Fig. 2.

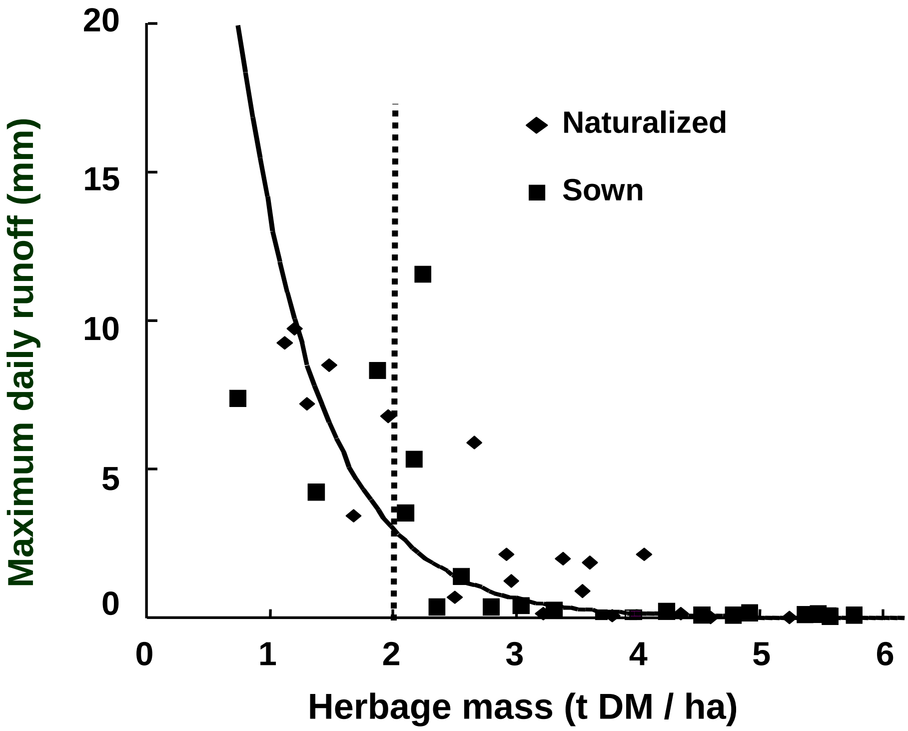

Naturalized
Sown
Maximum daily runoff (mm)
Herbage mass (t DM / ha)
0
5
10
15
20
0
1
2
3
4
5
6

Fig. 3.

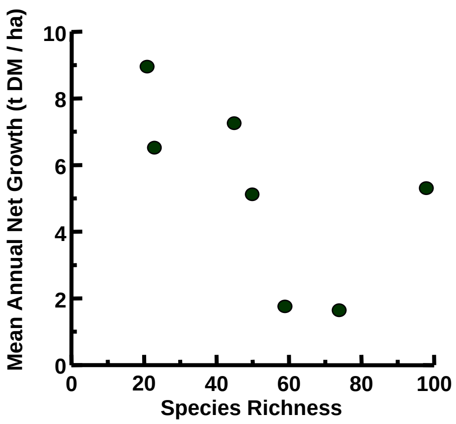

Mean Annual Net Growth (t DM / ha)
10
8
6
4
2
0
0
20
40
60
80
100
Species Richness

Fig. 4.

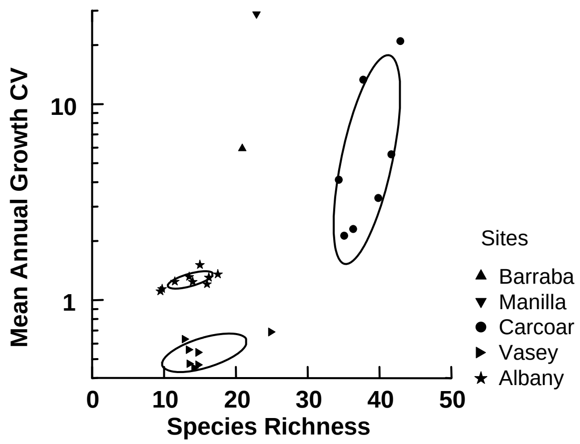

Mean Annual Growth CV
10
1
0
10
20
30
40
50
Species Richness
Sites
Barraba
Manilla
Carcoar
Vasey
Albany

Fig. 5.

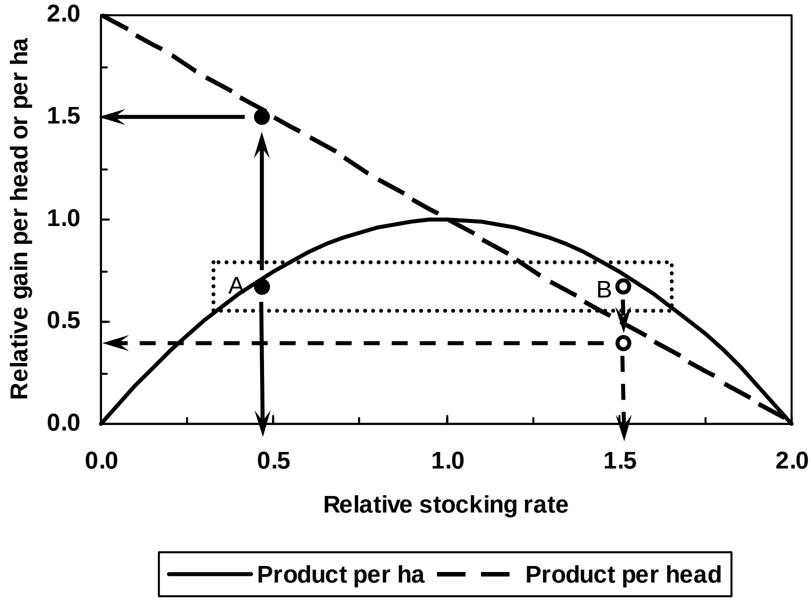

2.0
1.5
1.0
0.5
0.0
Relative gain per head or per ha
A
B
0.0
0.5
1.0
1.5
2.0
Relative stocking rate
Product per ha
Product per head

Fig. 6.