SOIL CONSERVATION AND LANDSCAPE PROCESSES IN AUSTRALIA'S RANGELANDS AND SAVANNAS

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Abstract
Australia's tropical savannas, and semi-arid and arid rangelands have soils of notoriously low fertility in an environment of highly variable rainfall. Land values are low and restoration of degraded land is generally prohibitively expensive. There is a widespread commitment to sustainably using the resources of outback Australia, but people face the difficulty of balancing the short term requirements to earn a living and the longer term challenges of environments that are remote, highly variable in time and space, and often poorly understood. Pressure from domestic stock, feral animals and in places enhanced number of native grazers has put ecosystems under pressure and lead to soil degradation. Land clearing has also affected some areas. Sustainable land management practices must aim at maintaining soil processes that underpin productive ecosystems. This requires a focus on fertile landscape patches that range in scales from perennial grass tussocks to mulga groves and to vast floodplains. The biological activity that ensures nutrient availability and water infiltration in those patches must be maintained. Sustainable management will only come about through partnerships between land managers, researchers, policy-makers and the monitoring authorities. The challenge of achieving this across the vast range of stakeholders in land management remains before us, but for much of the outback, it is not yet too late.

Additional Keywords: arid, semi-arid, grazing, cattle, sheep.

Introduction
This paper focuses on issues affecting soil conservation in outback Australia. This area constitutes most of the continent, ranging from semi-arid winter rainfall areas in the south, to the arid aseasonal centre and north to the wet-dry tropics. I briefly review the social drivers of outback Australia, with much of the information in that section being derived from The National Land and Water Resources Audit (http://www.nlwra.gov.au/) and the Australian Natural Atlas http://audit.ea.gov.au/ANRA/atlas_home.cfm). The physical environmental is then overviewed with attention to the geomorphological setting of the soil resource and the importance of rainfall regimes and water availability. Key landscape processes that sustain the soil resources are then considered. Finally, I present the challenge of integrating the social, environmental and process-driven complexities into management systems that sustain the soil resource in Australian rangelands and savannas.

Social Drivers in Australian Rangelands and Savannas
Pastoralism is the dominant industry in Australia's rangelands and savannas in terms of land area. Sheep are grazed for wool in the south and beef cattle raised in the north, often for live export. Much land is also used for traditional purposes by Aboriginal people, and substantial areas of Western Australia remain unallocated Crown Land. The Australian outback has one of the lowest human population densities in the world, which has important ramifications for soil conservation. In the more populated south-east and south-west of the continent, farm sizes are usually less than 50 km^2, but in the Northern Territory and much of Western Australia, properties are typically larger than 650 km^2. In some areas, the small size of properties exposes landholders to a high risk of having to sacrifice long-term sustainability for short-term productivity. In other areas, large properties make management of grazing pressure difficult, with resulting overgrazing typically around water points. Remoteness and a difficulty in accessing community services are major issues for people living in outback Australia. Community debate about the provision of services such as communication, medicine and banking to remote areas remains ongoing.

The proportion of indigenous people in the population is far greater in outback Australia than in the cities. For example, about 25 % of the Northern Territory population are Aboriginal, with more than 50 % of the land being Aboriginal owned under various tenures. Aboriginal populations are generally younger than non-Aboriginal populations, because of higher birth rates. Retention of traditional knowledge is an important issue, with many elders being concerned to engage younger generations in land management.

Within the non-Aboriginal population, a high rate of turnover of personnel creates difficulties in maintaining corporate knowledge in the north and west of Australia. In other areas, grazing properties are more likely to have been in families for several generations. Concerns about perceptions of declining rural incomes and inaccessible services are probably behind the aging of farmers in Australia. From 1986 to 1996, the median age of farmers increased from 40 years old to about 50 years old.

There is a high level of indebtedness in many areas, which creates pressure for short-term decision making. Nevertheless, there is a strong commitment to Landcare issues with more than half of farms being members of Landcare groups in the north and west of the continent, and Landcare-related works being undertaken across Australia.

Environmental Overview: Dry, flat and Infertile

Compared to the rest of the world, Australia has a low and highly variable rainfall. The El Nino southern Oscillation is responsible for cycles of droughts and floods that beset many areas. The dominance of closed depressions and evaporation to the Australian water budget results in the proportion of rainwater to flowing to the sea being the lowest of all the inhabited continents (McLennan, 1998). Consequently salinity risk is very high.

Australia is the flattest of the continents, with low rates of erosion at geological time scales. Soils are old and impoverished with concentrations of total nitrogen in Australian arid zone soils being about one half that of equivalent soils overseas and of total phosphorus being about one third (Stafford Smith and Morton, 1990). In arid Australia, exceptionally high rainfall events are major creators of landscape structure, establishing the patterns of fertile alluvial soils on floodplains and floodouts. Compared with infertile area, these fertile landscape elements can have four times the available nitrogen and phosphorus (Stafford Smith and Morton, 1990). Most of the available fertility is contained in the top few centimetres of soil. With soils of low fertility, forage of poor quality and water availability highly variable, outback Australia naturally supports few native grazing mammals. It is only the provision of artificial water sources and supplementary feeding that has allowed the development of commercial grazing, and facilitated increasing densities of macropods in the semi-arid lands particularly south of the Tropic of Capricorn. When cattle and sheep first spread across Australia, their impact was centred on lands fronting permanent water holes in rivers (Condon, 1972). Streambank erosion, gullying and sheet erosion following the combined effects of removal of grass cover and high intensity rains affected many locations. This was exacerbated by periodic droughts. Grazing pressure is now centred on the artificial water supplies and declines outwards. This has created a new spatial heterogeneity unseen in Australia prior to European settlement. Managing spatial heterogeneity to maximise production while maintaining landscape function and biodiversity remains a challenge.

Soil Water Availability: a Key Driver

Rainfall regimes vary from winter dominant in the south to summer dominant in the north, with a seasonal rainfall dominating the arid interior. Rainfall erosivity is greatest in the tropical north.

The wet-dry tropics of the world are characterised by warm temperatures throughout the year, with a summer rainy season and often negligible rain during the winter dry season. In southern and west Africa and north Australia, where topography is subdued, marked gradients of decreasing rainfall follow increasing latitude. More complicated gradients occur in other parts of Africa, South America and eastern Australia (Műller, 1982). Although many characteristics of the vegetation are correlated with the amount of rainfall, it is not necessarily total rainfall that is the key driver of vegetation dynamics. The length of the dry season, and by corollary, the length of the wet season probably has major functional significance. Nevertheless, the seasonal patterns of rainfall are often highly confounded with the amounts, making disentanglement of the key processes difficult.

Northern Australia has arguably the longest dry season with the highest amount of rain of almost anywhere in the tropics. For example, Pirlangimpi on Melville Island receives an average of 2019 mm, but less than 8 % occurs during the six driest months. Most meteorological and climatological research in north Australia has focussed on the major synoptic-scale events that lead to the bulk of wet season rainfall. The southward movement of the climatic equator and the onset of the summer monsoon are the main contributors to these events. However, for terrestrial vegetation, the amount of rain during the central period of the wet season is probably irrelevant. There is usually more than enough. It is the occurrence of the isolated storm events that mark the functional end of the dry season (Cook and Heerdegen, 2001). The timing of the last rain-bearing storm of the wet season is similarly important in setting the length of time that the vegetation must rely on stored soil water.

While global circulation and climatic drivers are responsible for the variations in temporal patterns of rainfall across the planet, human management can greatly alter the effective amount of rainfall available to plants. More precisely, management can alter the capture of rainwater by the soil and this will have its greatest effect when rain is falling in high intensity storms rather than during low intensity events or during prolonged monsoonal periods or from rain depressions. Measurements of the effects of fire regime on stream runoff at Kapalga in Kakadu National Park, Northern Territory Australia show no runoff and therefore complete infiltration from an unburnt catchment, and significant runoff from a catchment burnt late in the dry season (Townsend and Douglas 2000). Later in the season, when vegetation is growing strongly and the greater frequency and magnitude of rainfall events is greater, no differences were apparent. Bare soil at the time of early storms increases the length of the dry season by reducing water capture by landscapes.

The export of salinity, suspended solids and nutrients to waterways increases sharply when more than 50 % of a landscape is cleared due to changes in soil hydrology (Harris, 2001). Nevertheless, even in uncleared catchments, any loss of the ability of landscapes to capture and retain resources will have important downstream consequences. Sediment flow into the Great Barrier Reef lagoon from the Burdekin River increased as soon as European settlement and commercial grazing commenced in the catchment in the 1870s (McColloch *et al.*, 2003). The resulting increases in nutrient run-off has led to higher levels of phytoplankton, which in turn contributes to increasing frequencies of outbreaks of the coral-eating crown-of-thorns starfish (Brodie *et al.*, 2004; De'ath *et al.*, 2004). Clearly there is a national and international imperative to minimise any such damage to this World Heritage listed biological treasure. Nevertheless, the downstream impacts of one landholder's actions can be difficult to measure and ascribe to particular management decisions. Increased turbidity and eutrophication of reef waters may be occurring many hundreds of kilometres downstream from properties where soil was eroded. Land management that serves the national interest is most easily achieved when it also gives demonstrable and achievable benefits to individual landholders. Research that focuses on such goals is more likely to benefit both individual landholders and the national interest.

Functional Heterogeneity

In arid and semi-arid ecosystems, spatial heterogeneity can function to increase overall productivity because of the non-linearity of the response of production to resource availability (Noy-Meir, 1981). Perennial patches of vegetation ranging in scales from grass clumps to log mounds and mulga groves, and rich ephemeral floodplains and wetlands are islands of fertility in otherwise impoverished landscapes. Degradation occurs through homogenisation of landscapes and the loss of resources from the fertile islands (Tongway and Ludwig, 1997).

Obstructions to water flow and protection of the soil surface from raindrop impact, such as those provided by perennial patches of vegetation and log mounds are critical to increasing infiltration and reducing runoff. In many arid through semi-arid to mesic ecosystems, a functional heterogeneity exists at the landscape level with perennial patches depending on runoff from bare to semi-bare interpatch zones (Ludwig and Tongway, 1997). A loss of this heterogeneity through overgrazing, overburning or overclearing degrades the system with resulting reduced productivity and a downslope loss of nutrients, water, carbon and soil.

Macroinvertebrates: Ploughs in Untilled Soil

Invertebrates represent the vast majority of the earth's species and regulate a vast range of essential processes in the cycling of water and nutrients. They drive many key soil processes in Australian rangelands and savannas. Their activity is focussed on perennial patches, which are sites of most primary productivity, aside from the function of these patches in providing physical barriers to movement of water and wind.

Macroinvertebrates and especially earthworms, termites and ants create large pores in the soil that greatly increase the rate of water infiltration. The Poiseuille equation, which shows that the rate of volume flow of a liquid through a pipe increases with the fourth power of the diameter of that pipe, demonstrates the great significance of macroinvertebrate activity to hydrology. Many studies have shown that the loss of macroinvertebrate activity in arid and semiarid ecosystems reduces soil macroporosity, and consequently reduces water infiltration rates and the percentage capture of rainfall (Eldridge *et al.*, 2001).

In drier regions, termites and ants fulfil many of the roles fulfilled by earthworms in more mesic environments. Termite mounds dominate the landscape in many areas, but represent only the more obvious part of the termite fauna that includes arboreal and subterranean species. At millennial time scales, their mound building activities can create whole soil horizons (Holt *et al.*, 1980). However, of more immediate concern to landscape processes is their creation of patches enriched by organic matter, their ability to fix nitrogen through gut symbionts and the alteration of patterns of water infiltration through increasing porosity in some areas and decreasing it in others. Grass harvesting and litter feeding species of termites and to a lesser extent those feeding on lying dead wood are the most important in creating macropores that are hydrologically functional. The many groups that feed on the exterior and interior of trees are much less relevant to processes of water infiltration. Similarly terrestrial ants are of greater hydrological significance than are arboreal species. Ants, for whom Australia is home to the greatest diversity of species in the world, also play many roles in outback ecosystems: creating macropores, scavenging resources and harvesting seeds. Earthworms, not normally associated with seasonally dry ecosystems also contribute to the development of macroporosity, with their activity restricted to periods when soils are moist and concentrated on rich sites such as grass tussocks, log mounds and the bases of trees.

Recent studies in Darwin, Northern Territory (Dawes-Gromadzki and Cook, unpublished data) show that decreasing land condition was associated with increased dominance of the soil macroinvertebrate fauna by termites. They are one of the most hardy groups with a high ability to forage in crusted soils of high bulk density and to rely on food of low nutritional quality. Sites that had remained ungrazed in the Charter's Towers region of Queensland, Australia showed almost complete cover of the soil surface with earthworm casts compared with less than 5 % cover in grazed sites. Under high levels of grazing, the activity of earthworms was substantially reduced.

The importance of earthworms in soil formation was recognised by Darwin in the late 1800s. They are semi-aquatic animals that must maintain a moist cuticle to facilitate gas exchange (Lavelle and Spain, 2001). Consequently a wet-dry tropical climate presents considerable challenges, with high rates of earthworm death at the end of the wet season with soils becoming increasingly dry and resistant to penetration. Of the three main ecological types of earthworms, Anecics are those that will contribute most to water infiltration. The anecics create subvertical galleries within the soil that reach to the surface where they feed on litter. In contrast, epigeic worms eat and live within the litter and endogeic worms remain deeper in the soil. Although the galleries of endogeics can increase porosity and aeration deeper in the soil, they will have limited influence on hydrology unless the soil is saturated because water held under tension will not enter a subterranean pore. The anecics will contribute not only to the porosity and aeration of soils, but also to infiltration and drainage because free water on the soil surface can rapidly enter their large galleries. Unfortunately little is known about the anecic species and their ecology in the wet-dry tropics.

Because earthworms, termites and ants affect soil properties in different ways, and even within each group, there are substantial differences in their effects on soil properties. The impact of changing soil macroinvertebrate community structure on soil processes such as hydrology might not be directly correlated with vegetative cover. The potential lack of correlation of plant cover in rangelands with soil surface properties gave the rationale for recently developed systems of landscape function analysis. The practical consequence of this disjunction is that landscape function, defined as the ability of landscapes to capture and retain resources might be declining while pasture quality or economic productivity is being maintained, at least over short to medium time periods. Thus, analysis of plant cover or cattle live weight gain alone might be poor indicator of ecosystem trends. The long term consequence of a loss of landscape function will be a practically irreversible decline in productive potential, and by the time this is apparent it is likely to be too late for cost-effective action.

A better understanding of the how macroinvertebrates respond to management, and the consequences of that response for the soil could indicate ways to manage the savanna rangelands to maintain both productivity and landscape function. Further, the ability of earthworms, termites and ants to convert vegetation into functional macroporosity in soils could present a very efficient means of restoring landscape function to degraded or reconstructed ecosystems.

Incorporating knowledge across scales from a termite hole for example to a hillslope, then to a small water course and up to rivers and estuaries will require the use of computer simulation models. Perenial patches and interpatches are the scale at which macroinvertebrates forage and influence soil hydrology (Ludwig *et al*., in press). While differences in water infiltration rates at this scale may amount to several orders of magnitude, they translate to much less difference at the hillslope scale due to runoff from a site of low infiltration increasing the water available for infiltration in a downslope patch. The effects of differences in water availability for plant growth are also realised at this scale. Although cattle are at larger scales with paddocks often of a similar size to small catchments for temporary streams, they select their forage and impact landscape function at the scale of patch and interpatch. Moving to property and regional management and its impacts on hydrological processes requires the incorporation of economic and sociological drivers of decisions, as well as larger scale environmental determinants such as systematic climatological variation and geology.

Beyond the Black Stump.

Beyond the black stump is an Australian expression denoting land far from civilization, and actually refers to a burnt tree stump at Blackall, central Queensland used as a marker by surveyors as a datum in 1887. It epitomises the importance of fire to Australian ecology. With vast landscapes unbroken by large rivers, mountain ranges, heavily grazed areas or cities and cultivation, the Australian outback has long been subjected to frequent extensive fires. Fire is critical to the utilisation of soil resources by vegetation and has also played a key role in soil formation in Australia. Up to 30 % of soil carbon in Australian soil is finely divided charcoal is a major constituent of many Australian soils and probably contributes significantly to the inert or passive organic carbon pool (Skjemstad *et al*., 1996). Fires continue to dominate the ecology of north Australian savannas and the arid and semi-arid interior (Andersen *et al.*, 2003). In more densely settled eastern semiarid regions, intensive settlement and a desire to use grass for fodder rather than fuel has drastically reduced fire frequency from that before European settlement.

Frequent fires may cause a rundown in nutrient levels and particularly nitrogen in soils (Cook, 1994; Cook, 2001). Low nitrogen levels reduce the palatability of vegetation to herbivores and can alter the floristic balance. However, the interactive effects of fire on the use of soil resources by trees and grass is perhaps the major influence of burning regimes. The balance between trees and grass is one of the key dynamics of savannas and arid landscapes. Seedling recruitment by trees is rare and typically occurs when soil water regimes are favourable for seedling persistence. By removing competing vegetation, fire can create sites for the establishment of tree seedlings, or can kill seedlings. The interactions are complex and poorly understood for most ecosystems across Australia. The consequences of changing tree to grass ratios for nutrient cycling and soil water relations are great. Increasing tree density will increase water use by landscapes and reduce runoff, while decreasing tree density may reduce nutrient recycling from deeper soil layers.

The Future

The Australian outback is characterised by a highly variable rainfall regime, inherently poor soils interspersed with fertile patches, a sparse human population and low land values. Traditional soil conservation works such as cultivation and the sowing of introduced perennial plant species is expensive and of questionable success at addressing large scale problems (Condon, 1972; De Salis, 1982; Ryan, 1981). Further, the deliberate planting of exotic species is fraught with potential conflicts, with history showing many becoming unwanted weeds (Lonsdale, 1994). Management of this landscape must aim to conserve the resources that are there. Restoration can rarely be pursued. Management must be based on a sound understanding of the processes that maintain the soil resources fundamental to productivity. The time scales of these processes vary from decades and centuries for major variations in rainfall regime to minutes, hours and days for rainfall events, soil water recharge and runoff. Spatial scales vary from the spaces between grass tussocks to tree groves and landscape patterns across hundreds of kilometres. The tools to monitor these landscapes must therefore range from satellite imagery to long term climate data to measures of millimetre change in soil erosion fronts. Sustainable management will only come about through partnerships between land managers, researchers, policy-makers and the monitoring authorities. The challenge of achieving this across the vast range of stakeholders in land management remains before us, but for much of the outback, it is not yet too late.

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