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Sustaining productive pastures in the tropics
1. Managing the soil resource

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Abstract

The grazing of pasture systems has many of the elements essential to a sustainable agro-ecosystem wherein the soil resource is not degraded through time. Unfortunately there is increasing evidence that the soils of Australian tropical grasslands are suffering serious and permanent degradation through our inability to manage grazing pressure under the highly variable climatic regime which characterizes the Australian tropics.

This paper details the evidence of soil degradation under our current rangeland management and illustrates how far these practices are from that of a sustainable system. The challenge to find grazing systems that are sustainable is shown to lie in recognizing that the soil-plant-animal ecosystem must be studied in an integrated way. Focus on short term animal productivity without consideration of the consequences to all other essential components of the ecosystem is shown to be a primary cause for degradation of the soil resource. Too often the consequences of a practice has not been considered because the components of the agricultural system have been studied in isolation.

Both salinity and soil acidification are identified as soil resource management issues that must receive attention in the Australian tropics. The use of tropical legumes, the clearing of woodlands, and the use of introduced grasses are all managements that can radically alter the flux of water, nutrient and salt in the soil profile. The management of these factors is the key to control of both salinity, and soil acidification. The place and balance of the grass, legume, shrub and tree is fundamental. Progress in building sustainable grazing systems in the tropics requires integrated ecological studies with increasing emphasis on both the role of soil biology in the cycling of nutrients and the movement of water and solute in the system.

Resumen

Los sistemas de pastoreo tienen muchos elementos esenciales propios de un agro-sistema sostenido en el cual el recurso suelo no se degrada a través del tiempo. Desafortunadamente hay evidencias que indican que el suelo de los pastizales de Australia están sufriendo una seria y permanente degradación debido a nuestra inhabilidad para manejar las presiones de pastoreo en un régimen climático muy variable característico del trópico de Australia.

En el presente artículo se detallan las evidencias de la degradación del suelo bajo el actual manejo de los pastizales asimismo se ilustra lo lejano de tales prácticas del sistema de producción sostenida. El reto para encontrar los sistemas de pastoreo que sean sostenibles radica en el reconocimiento de la necesidad de estudiar el ecosistema suelo-planta-animal en una forma integral. Se ha demostrado que el énfasis en la productividad animal a corto plazo sin la consideración de las consecuencias en todos los demás componentes del ecosistema ha sido la causa primaria de la degradación del recurso suelo. Muy frecuentemente no se consideran las consecuencias de una práctica de manejo, debido a que los componentes de los sistemas agrícolas han sido estudiados en una forma aislada

Tanto la salinidad como la acidificación del suelo son identificados como materia del manejo de los recursos que debieran recibir atención en los trópicos australianos. El uso de leguminosas tropicales, las remoción de árboles, y el uso de gramíneas introducidas son prácticas de manejo que pueden radicalmente alterar el flujo de agua,

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nutrientes y sal en el perfil del suelo. El manejo de estos factores es la clave para el control de la salinidad y la acidificación del suelo. La posición y el balance de la gramínea, la leguminosa, los arbustos y árboles es fundamental. El progreso de la elaboración de un sistema de pastoreo sostenido en los trópicos requiere de estudios ecológicos integrales con un creciente énfasis en el papel de la biología del suelo sobre el ciclo de nutrientes y en el movimiento de agua y solubles en el ecosistema.

Introduction

At a first glance it might be expected that grazing of native or introduced pastures should have the elements essential to a sustainable agro-ecosystem wherein the quality of the soil resource is maintained over the long term. On closer examination of the grazing systems in tropical Australia there is increasing evidence that few if any of our systems are sustainable agro-ecosystems in their present configurations.

It has been rare for agricultural research to consider the production system from the view point of the ecosystem into which it has been cast. The emphasis and purpose of most agricultural research and development is improvement in short term productivity. The way in which the production system interacts with the hydrological and nutrient balances and the implications of these interactions for the longer term stability and sustainability is usually neglected or studied in isolation from the production system. The consequence of this is the general failure of the agricultural community to appreciate the place of their farming system in their regional ecology.

The forms of land degradation that are important in tropical Australia will be dealt with in more detail subsequently, however all can be seen to result directly from interference with hydrological and nutrient cycles that were previously in balance in the virgin landscape. The effects we call degradation are in fact changes to the land system so that a new balance can be established. Movement towards equilibrium will occur but the new equilibrium state may not be compatible with productive agriculture. If land degradation can be viewed in this general context it will assist us greatly in understanding the direction we must take in order to move towards a sustainable agriculture, one that is productive and one which is in balance with the nutrient and hydrological cycles in which it is cast.

Some properties of sustainable agro-ecosystems

To set the framework for discussion of managing the soil resource within a sustainable agro-ecosystem it is important to set down some of the principle elements that can be used to define a sustainable system. Figure 1 sets out flow of matter and energy in a generalized natural ecosystem. A sustainable ecosystem will be characterized by:

- a very large amount of cycling of matter between the soil and the food web of the community
- the inputs and outputs of matter are essentially in balance.

The base line situation that exists in natural ecosystems is well put by Aldo Leopold when he states: "For every atom lost to the sea, the prairie pulls another out of the decaying rocks. The only certain truth is that its creatures must suck hard, live fast, die often, lest it losses exceed its gains."

Most natural ecosystems therefore tend to approach closed systems where inputs balance outputs, however those actively growing systems like the famous Hubbard Brook Forest gain more than they lose. A declining or degrading ecosystem or one that has been disturbed loses more than it gains.

In Figure 2 the energy and matter flows are shown in a natural ecosystems, an agro-ecosystem, and an urban ecosystem. The key issues to note are that as we move from a natural ecosystem to an agro-ecosystem the balance between inputs and outputs is no longer closed and the cycling of matter between the community and the non-living surroundings decreases significantly. In the urban ecosystem the balance between inputs and outputs changes and there is little if any cycling.

An ecologically sustainable farming system needs to be considered in these terms and frameworks. A primary requirement of a sustainable farming system is that the nutrient inputs and outputs are balanced and that the nutrients and organic matter cycle as rapidly as possible in the soil-plant-animal system. The closest that this mass balance can be satisfied is set by fundamental geological processes, wherein loss of nutrient to the sediments and waters of the oceans is met by supply of nutrient from the weathering rock.

The non-living surrounding of the ecosystem is essentially the physical, chemical and mineralogical components of the soil resource. Thus the condition of the soil in any agro-

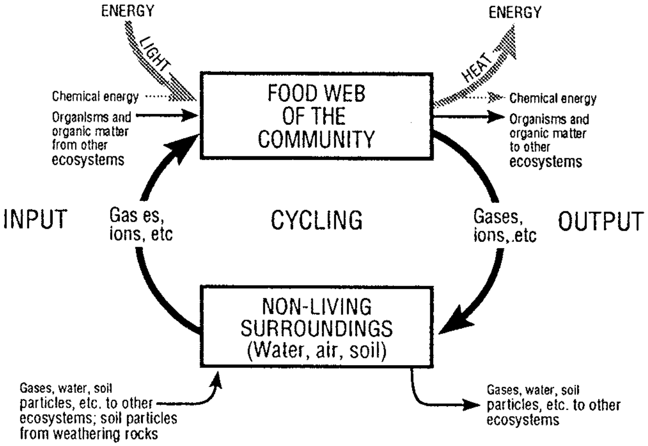

Figure 1. The generalized flow of energy and matter in a natural ecosystem.

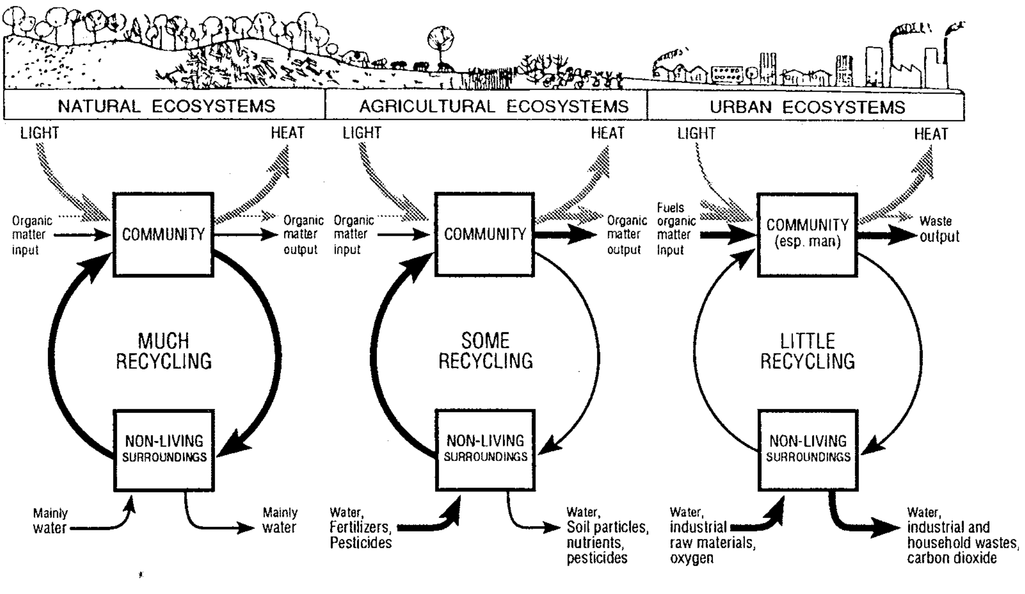

Figure 2. A comparison of the energy and matter flows in natural, agricultural and urban ecosystems. Sustainable ecosystems will maximize cycling of matter and be closed or positive in terms of matter balance.

ecosystem will reflect how closely the system conforms to the sustainability criteria. The degradation of the soil resource in terms of nutrient depletion, soil structure decline, soil acidification and biological decline are testimony to the fact most Australian farming systems are far from sustainable. The state of the soil resource under current grazing management in the Australian tropics is a measure of the ecological sustainability of our grazing systems.

The ecological requirement for a balance between inputs and outputs and maximum cycling of nutrients within an agro-ecosystem are static criteria. Other important criteria for a sustainable ecosystem relate to the dynamic condition of the soil resource. Consider the nutrient cycle for an agro-ecosystem as set out in Figure 3 and the manner in which it responds to applied stress. When the outputs exceed the inputs for a nutrient over a given interval of time then the

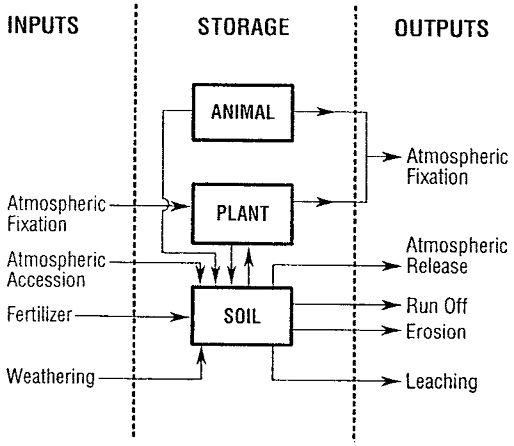

Figure 3. The nutrient cycle for an agricultural ecosystem showing the nutrient inputs, the storage of nutrient and the output of nutrients. For a sustainable system the inputs must balance the outputs.

nutrient status of the soil must decline. The manner in which a soil property declines and then recovers under management is a very important measure of sustainability. The magnitude of the decline relative to the limit of sustainability and the rate of recovery or the elasticity, are two key measures of sustainability. The limit of sustainability is the state beyond which the property cannot make recovery and the rate of recovery is a measure of the elasticity of the system. These concepts of sustainability are depicted in Figure 4.

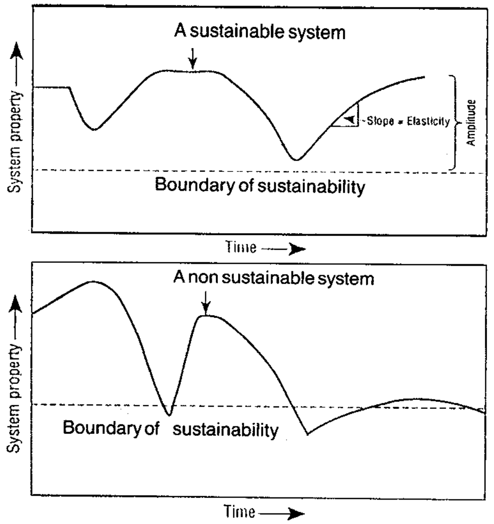

Figure 4. Concepts of sustainability. The amplitude and the elasticity of the response of the system property to applied stress for both a sustainable and a non-sustainable system.

With these concepts in place we can set in perspective the issues of soil management under grazing which currently require attention in the search for sustainable grazing systems in the Australian tropics.

Soil management issues for sustainable grazing systems

Soil degradation is assuming increasing importance in Australian agriculture. Acidification of the profile and structural decline are now high on the agenda. The problems of erosion and salinity will become increasing problems in Northern Australia as the northern agriculture ages and sufficient time elapses for the problems to manifest themselves.

These problems are however not new to Australian grazing industries. The first signs were there as early as 1901 when a Royal Commission was set up to look into the problem of the decline in pasture quantity and quality and an increase in woody weeds. The description of the degradation that is present in our rangeland is well described by James Cotton in his statement to the 1901 Royal Commission. In that he stated "There has been a gradual deterioration of the country caused by stock which has transformed the land from its original soft, spongy, absorbent nature to a hard, clayey, smooth surface which instead of absorbing the rain, runs it off in a sheet as fast as it falls carrying with it the surface mould, seeds of all kinds of plants, sheep manure, sand etc, to enrich the lower lying country and plant it with pine, box, and other noxious shrubs." Conservative estimates (Commonwealth and State Governments 1978) indicate that approximately 43.2 million hectares or 13% of our pastoral land are seriously eroded wherein soil loss can be exceeding 20 tonnes/ha/yr. The current QDPI/CSIRO land degradation survey (De Corte *et al.* 1991) of the Dalrymple Shire (6.7 million hectares in North Queensland), found that in excess of 80% of sites examined suffered significant soil erosion. In comparison to the area of erosion under cropping or the areas suffering salinization the areal extent of the erosion in our pastural rangeland is massive.

Soil infiltration properties, hydrology and erosion

It is the perturbation of the hydrological cycle (see Figure 5) which was balanced in the virgin landscape, that is the primary cause of soil erosion and salinity which has flowed from temperate Australian farming practice. The hydrological changes are often subtle and the implications of the change are not often manifest in the short term. When the farming system replaces native woodland and perennial grasses with crops and annual pastures the evapotranspiration term is usually reduced with the result that the deep drainage and runoff terms must increase for the cycle to find a new balance. The consequence of this change is to increase the likelihood of erosion and salinity. Under legume pastures the increase in deep drainage will mean loss of nitrate and with it basic cations, and therefore exacerbate the acidification of the profile.

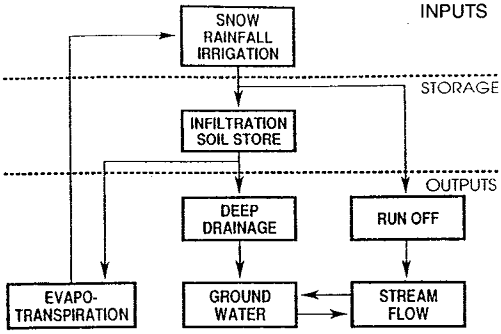

Figure 5. The hydrological cycle for an agricultural ecosystem, illustrating the inputs of water, storage of water in the soil, and the outputs of water in either drainage beneath the plant roots to groundwater, runoff, streamflow and evapotranspiration. The inputs and the outputs seek a balance.

In the semi-arid tropics of northern Australia much of our understanding of the effects of grazing comes from specific experiments involving recovery after grazing, exclosures, or fenceline contrasts. Bridge *et al.* (1983) showed that after dry season burning and weekly clippings to stimulate grazing during the following two wet seasons a number of soil properties of red earths near Katherine in the Northern Territory were affected deleteriously. Infiltration measurements showed that sorptivity and hydraulic conductivity were greatly reduced after the first wet season following burning. Micromorphological examination showed surface sealing and structural collapse. Although sorptivity recovered after the second wet season, hydraulic conductivity did not and a vesicular porous layer typical of many crusted soils formed in the top 5 mm. The authors also noted death of grass tussocks, followed by a loss of soil organic carbon during the second season. Their work demonstrated that complete degradation with the formation of bare areas could occur due to overgrazing in as little as two years. These scalds are common in semi-arid, tropical environments. Their persistence is attributed to seed removal during runoff, to high temperatures and low water content in the sealing surface and to mechanical impedance preventing seedling emergence (Mott *et al.* 1979).

Further south near Wycanna in southern Queensland, Braunack and Walker (1985) conducted experiments to assess recovery after 100 years of impacts from sheep and cattle grazing on solodic soils in the semi-arid poplar box (*Eucalyptus populnea*) woodlands. This physical disturbance often results in the massive recruitment of generally inedible woody plants rather than grasses and results in lower productivity. In this environment, in spite of the greater protective canopy cover, removal of stock resulted in greater infiltration, an increase in soil surface porosity and increased levels of organic matter in the surface. Although a surface crust did not develop under grazing on the soils in question, a hard-setting condition was apparent.

Burch (1986) documents substantial reductions in saturated hydraulic conductivity and long term infiltration rate as consequence of grazing cleared poplar box woodlands in Southern Queensland. The consequence of grazing was greatest in the inter-tree areas where the infiltration rates and saturated hydraulic conductivities were decreased by a factor of three. This suggests that killing trees and grazing in these native woodlands can be expected to reduce the broadscale permeability of soils, particularly the duplex soils and to promote increased run-off and surface erosion. Bonell and Williams (1986) show that run-off is negligible under little disturbed eucalypt woodland but can be up to 30% of rainfall under heavily grazed legume pasture on red earths in Northern Australia (Ive *et al.* 1976). Again the infiltration rates under grazing decrease by a factor of four from 80 mm/hr to 15 mm/hr. The surface roughness and thus the surface detention store is a factor in addition to the infiltration rate that is most important in interpreting the consequence of grazing on surface hydrology.

The physical compaction effect of trampling by stock is readily apparent around watering points. Marshall (1974) provides some data on the effect of trampling intensity on sorptivity and steady state infiltration rate. Sorptivity declined by a factor of three to reach a plateau at a value that approximated that found in scalded areas. The infiltration rate declined by a factor of four from the stable soil surface near saltbush to that found on a sheep track. It should be noted that Williams and Bonell (1988) found a six to ten fold difference in infiltration rates between areas near spinifex tussocks and bare areas of soil between tussocks in a little disturbed woodland. This would indicate that the decrease in surface infiltration properties caused by trampling on tracks is of the same order as the increase in infiltration properties that result from soil organism activity associated with tussock vegetation. Grazing of stock on our rangelands not only appears to cause a decrease in infiltration rate but grazing increases spatial variability of the infiltration rates operating in the landscape. This will have important consequences to the surface hydrology.

Studies conducted on red earths in the semi-arid rangelands of NSW near Cobar (Mücher *et al.* 1988; Chartres and Mücher 1989; Greene and Tongway 1989) have illustrated the nature and consequences of soil structural decline in ecologically sensitive environments following overgrazing. At the experimental site used by the above authors, a patchwork pattern of non-eroded (Class 1) to seriously eroded (Class 4) soil surfaces could be identified. Physically, Class 1 soils had significantly higher aggregate stabilities and higher infiltration rates than Class 4 soils for water entry at a supply potential of + 10 mm (macropore flow) (Greene and Tongway 1989). This was supported by micromorphological evidence of changes in macroporosity and cryptogamic plant cover, and greater erodibility of bare surfaces under simulated rainfall conditions (Mucher *et al.* 1988; Chartres and Mucher 1989). Crusting was significant in the most eroded classes and as in the work reported from the Northern Territory (Bridge *et al.* 1983; Mott *et al.* 1979) appeared to have a marked effect on seed lodgement, germination and the production of runoff. Elsewhere in the semi-arid zone of South Australia studies such as that of Graetz and Tongway (1986) have demonstrated similar changes in surface soil properties on adjacent sides of fencelines subjected to different grazing intensities.

Soil erosion in our farming system remains a national problem and must be addressed (Williams *et al.* 1985). It is common (Malik 1988) for agriculturalists and engineers to claim that all the answers to controlling erosion are known and we need only to implement the solutions. We are not so optimstic. We doubt, particularly in the tropics, if we have solutions which can handle the catastrophic events, which are the few events that cause most of the loss in sediments and nutrients. To build a sustainable farming practice that controls soil loss particularly in catastrophic events requires that the hydrological cycle be very similar to what it was under virgin conditions. The slopes' surface roughness and soil infiltration properties of the virgin landscapes were essentially matched to the rainfall intensity such that overland flow was minimized. This is a fundamental concept in geomorphology and is discussed to some extent in Bonell and Williams (1989) in that stable land-surfaces approach equilibrium with climate. As documented above grazing has generally reduced surface roughness, and infiltration rates and thus increased overland flow. Most of our current practices of contour banking do not address the basic change that has been made in soil infiltration, roughness and surface detention associated with vegetation. While the contour banks do increase the larger scale roughness and the surface detention they do nothing to halt the erosion process at the water-soil interface. Contour banks do trap sediment, but rills between banks are testimony to their failure to control the basic erosion process. To solve the problem of erosion control at its roots we must address the causes of the increased overland flow, its higher velocity and its shallower depths.

Because erosion is a major source of lost nutrients (Williams 1991), it is clear that any sustainable grazing system must aim to manage the water so that overland flow is reduced to at least what it was in the virgin landscape. The management of pasture, cover and form, soil surface roughness, and macroporosity through soil biology, are the keys to building a sustainable grazing system (Gardiner *et al.* 1990). We need to see erosion as part of managing the water in a balanced hydrological cycle, within which the grazing system must sit.

Dryland salinity and tree clearing

Whilst the national concern with salinization of agricultural lands is considerable (Malik 1988) the areas are small (Williamson 1990) compared to other forms of land degradation. However the area of salinity is increasing and can be expected to increase in the future as the salinization processes now in place because of past land use, express themselves in salinity outbreaks and increased river and stream salinity. It is in Western Australia (443,000 ha) and Victoria (244,000 ha) that dryland salinity are most extensive but the problem is assuming increasing importance in South Australia, NSW and Queensland.

Salinization under both irrigation and dryland farming is the consequence of the farming system disturbing the hydrological cycle that was in balance in the virgin landscape (see Figure 5). In particular, clearing of our forests and woodlands for crops and pastures usually results in less water use by the replacement vegetation and thus more water must move through the profile past the root zone. This water enters the regional groundwater system and causes the watertable to rise and seepage area to develop at the lower points, and at break of slopes, in the landscape. Salt in the soil profile or in the groundwater system is relocated to the newly established seepage areas. At these lower points or seepage areas the salt accumulates following evaporation. If the replacement vegetation used water in the same manner as the virgin vegetation and there were no changes in soil infiltration properties or surface roughness, there would be little problem.

Allison and Peck (1987) have shown that the amount of additional deep drainage or recharge sufficient to cause salinization can range from less than 5 mm/yr (e.g. in the Victorian Mallee region) to greater than 130 mm/yr as was the case following clearance of the forests of south western Australia. Although the above mechanism does tend to provide a common explanation for soil and stream salinization, each catchment situation can be complicated by other factors. To understand the hydrological consequences of clearing it is necessary to appreciate the fate of deep drainage, salt distributions in the landscapes and the movement of the regional water tables. Without this information the long term consequences of clearing is most uncertain. At the moment there are no routine methods that can evaluate the likely consequences of tree clearing in regard to salinization or other land degradation.

An understanding of the basic causes and processes associated with dryland salinity requires comprehensive appreciation of groundwater processes operating, land form, soils, geomorphology, geology, climate and land management within each region or catchment affected.

A further problem associated with dryland salinization is that the hydrological response to tree clearing whilst in some cases is rapid, elsewhere may be very slow taking many decades for the effect to be manifested. This poses special problems in the design of sustainable farming systems. The changes to the hydrological balance are so subtle that they are usually disregarded, yet in time these changes may cause the whole farming system to collapse.

Naturally saline soils are not extensive, occurring mainly in association with salt lakes in the drier regions of Australia. However, the secondary saline soils which form following clearing (or irrigation) are more closely associated with the sodic soils. Work done in Western Australia (e.g. Dimmock *et al.* 1974; Stokes *et al.* 1980; Bettenay *et al.* 1964) and Queensland (Gunn and Richardson 1979) show that the deeper subsoils in mottled and pallid zone materials contain substantial amounts of soluble salts ranging in amounts from 10 kg m^{-2} to 100 kg m^{-2}. This accumulation of stored salt may originate from several sources: the ocean via rainfall, weathering of soil and rock materials, and marine deposition in earlier geological periods (see review by Isbell *et al.* 1983). Following the clearing of upland 'lateritic' areas, saline seepages develop rapidly on slopes, particularly in certain higher rainfall areas of both Victoria (Jenkin 1981) and Queensland (Gunn 1967).

Salinization of streams and rivers as compared to soils is, however, a much more widespread phenomenon. For example, in areas where the extent of saline seepages is comparatively small, this effect on stream salinity and hence water quality may often be quite drastic. The patterns of subsurface water movement are often very complex in Australian landscapes. The groundwater may occur as an unconfined aquifer in one part of a catchment leading into a confined aquifer further down-slope due to the existence of layers (often palaeochannels) with different hydraulic properties.

The risks of dryland salinity following tree clearing in the Australian semi-arid tropics (Gillard, Williams and Moneypenny 1989) is a major issue which must be addressed. There is little basis for the view that while salinization as a consequence of clearing is a real concern in the temperate zone of Australia it poses a lesser threat in northern Australia (Burrows 1991). There is good evidence that the water balance in the monsoon regions of Australia can be characterized by substantial deep drainage and leaching of salts (Williams and Coventry 1979, 1981; Probert and Williams 1986; Chapman 1963; Wetselaar 1980; Jones *et al.* 1991). There are strong similarities between the water balances of mediterranean and monsoon tropical regions. As 70% of the annual rainfall is concentrated over the three months of wet season the opportunity exists for a close sequence of rainfall events to fully recharge the profile and generate water movement deep into the profile beyond the root zone. Probert and Williams (1986) show that there was a 50% probability of deep drainage exceeding 25 mm per year when trees are removed and replaced with *Stylosanthes* pasture and native grasses. Their data showed clear experimental evidence of substantial movement of nitrate down the profile. Figure 6 sets out the effect of tree killing and pasture development on the water use at the study site reported by Probert and Williams (1986). The large amount of water remaining in the profile at the end of the wet season as a consequence of tree killing is available to contribute to deep drainage. The recent work of Thorburn *et al.* (1991) showed that the substantial increases in deep drainage and movement of salt can take place immediately following clearing of Brigalow (*Acacia harpophylla*) in a subtropical environment where winter rainfall is significant. The opportunity for tree clearing to increase deep drainage in the monsoon tropical regions of Australia is substantial. Thompson (1980) describes a toposequence salinization process that is a feature of the lower Burdekin Region. He warned of the risks of tree clearing on the neutral red duplex soils which occupy significant areas of the Burdekin catchment.

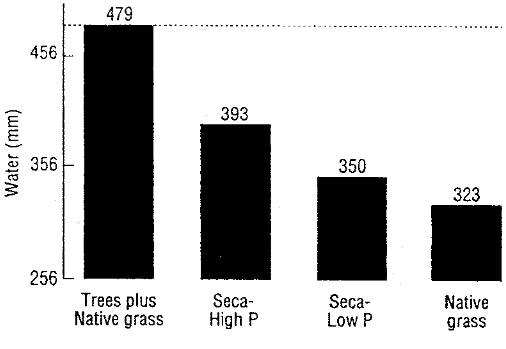

Figure 6. A comparison of water use by woodland and the effect of tree killing and pasture development on water use at the site reported by Probert and Williams (1986).

There is evidence that there are extensive areas of soils and regoliths in the Australian tropics which contain significant salt reservoirs (Gunn 1967; Gunn and Richardson 1979). It follows that there is little ground for an optimistic view that tree clearing in tropical Australia will pose little risk of dryland salinity. The need for well designed studies to identify the sources of salt and the pathways of water movement in the landscapes of northern Australia is a top priority (see CSIRO Land and Water Care Program, Operational Plan 1991-1994). Largely, our tropical woodlands have not yet been cleared. Therefore we have the opportunity to manage our soil and vegetation resources in such a way to avoid the damage that continues to plague our established agricultural lands in the south.

The lesson is that apparently subtle changes to the land through grazing management can have significant longer term effects on the hydrological and nutrient balances. It is essential that the farming system be seen as part of the regional hydrological system. We must therefore recognize that salt or agricultural chemical washed out of the soil profile must end up somewhere else in the ecosystem, usually lower in the landscape or, in lakes, wetlands, rivers and streams. Many of our tropical grazing lands are part of catchments that drain into estuarine and reef ecosystems that are an important part of our national heritage. In managing our soil resource we must not neglect the offsite consequence of our action.

Soil acidification

Soil acidification occurs at a slow rate in natural ecosystems. The acids produced in organic and inorganic nutrient cycles are involved in forming soils from parent rocks, and in releasing to the soil solution the nutrients contained in those rocks. Once in solution they are available for absorption by plants and for leaching by water flowing through the soil. Soils that have been acidified in natural ecosystems are more prevalent in areas of higher rainfall, especially where the soil is old and where the parent materials are low in the basic minerals (e.g. carbonates and Ca and Mg silicates) that buffer the soil pH against acidification. Agricultural and pasture ecosystems are characterized by faster rates of acid addition because of the imposition of product removal, the addition of acidifying nitrogen fertilizers, and increased opportunities for nutrient leaching.

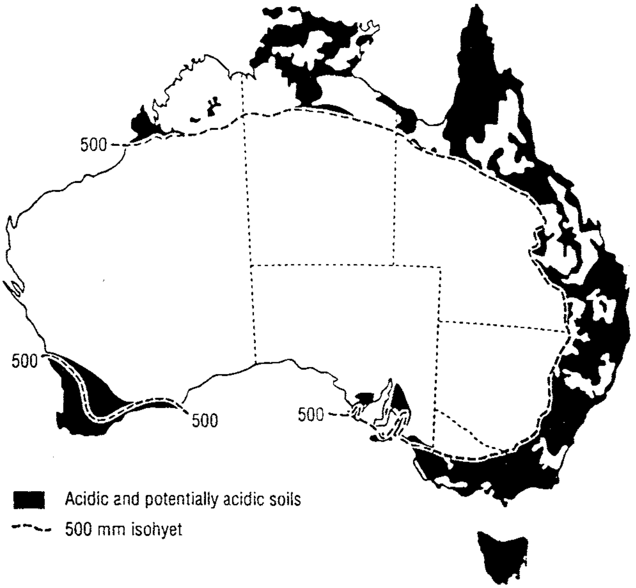

Figure 7. National distribution of acidic and potentially acidic soils above the 500 mm isohyet. (From Tiller and Merry 1989.)

These practices can increase the acid addition rate from levels probably as low as 0.5 kmol H + /ha/hr in natural ecosystems, to 20 kmol H + /ha/yr in extreme cases (Helyer and Porter 1989).

As a consequence of the above process a widespread condition of increasing acidity has developed in extensive areas of southern Australia under the seemingly stable system of permanent and ley legume pastures to which superphosphate additions are considered essential (Williams 1980). The decline in pH has been of the order of one pH unit over 50 years of pasture.

Organic matter accumulation and profile leaching of nitrate and with it basic cations from the profile are the most important processes which lead to acidification. Soils with pH dependent charge (Gillman and Bell 1976) which occupy extensive areas of tropical Australia will be most seriously affected. The fall in pH further reduces the capacity of these soils to hold those basic cations which are essential to plant nutrition. With decreasing pH, Al and Mn toxicity become increasingly important problems. The whole chemistry of the soil can be changed by the farming system that has been imposed. The degradation of soil through acidification will not be restricted to temperate pasture lands. Early evidence (M.E. Probert, personal communication) indicated a significant decline in pH after 5 years under pure swards of *Stylosanthes* grown in the semi-arid tropics of north Queensland on red and yellow earths. Recent work by Jones *et al.* (1991) demonstrates that substantial leaching of nitrate occurs under ley pasture/cropping system in northern Australia. Preliminary work by Tiller and Merry (1989) as set out in Figure 7 indicate that soils with potential to become acidic are extensive in the Australian Tropics. Soil acidity is not a problem of southern agriculture that can be ignored in the Australian tropics.

Acids produced in the N cycle are more significant in agricultural ecosystems because of increased nitrogen inputs as fertilizer and through accumulation of biologically fixed nitrogen. If these inputs are not matched to increases in plant demand, the result will be an accumulation of mineral nitrogen in the soil and increased opportunities for nitrate leaching or run-off. Estimates of the contribution of the N cycle to acidification under grazed annual pastures in the 500 to 700 mm rainfall zone of southern Australia, have been made indirectly by deducting the effects of carbon cycle acids from the total acid addition estimated from pH change and pHBC data (eg. Ridley *et al.* 1990a, 1990b; Helyar and Porter 1989). These indirect estimates range between

2 and 7 kmol H + /ha/yr. In these studies inclusion of the perennial grass phalaris in the pasture reduced acid addition rate by about 1 kmol H + /ha/yr. In other agricultural ecosystems nitrate leaching rates (kmol N/ha/yr) of 3 (Power *et al.* 1972), 0.4 to 4.0 (Gustafson 1987), and 2.9 to 7.1 (Martinez and Guiraud 1990) have been measured by various direct methods.

The water balance of monsoon tropical climates is generally conducive to leaching of nutrients (Probert and Williams 1986; Jones *et al.* 1991) for the reasons discussed above for salinity. Therefore it must be placed on notice that soil acidification under tropical pasture legumes must be an important issue in the management of the soil resource in the Australian tropics. It is worth emphasizing that the management of both soil salinity and soil acidification under pasture revolves around the management of water and nitrogen fluxes in the profile as a function of time by way of the sinks and sources provided by grasses, legumes and trees. The growth of these plants in response to water regime, temperature and photoperiod are the factors which determine when and where the nitrogen is generated and consumed.

The need for reliable water and nitrogen models that describe these processes under grasses, legumes, shrubs and trees is obvious if we are to seek out and find sustainable grazing systems. The role of our trees in cycling nitrate and cations from depth in the profile and the part that trees may play in providing a management tool for soil acidification requires clarification. It is another important factor in the debate on tree clearing in the woodlands of our monsoon tropics.

Managing soil organic matter

The decline in soil organic matter is frequently regarded as being the primary cause of most of the deleterious change to Australian soil that has occurred since European settlement particularly when viewed against the fact (Spain *et al.* 1983) that approximately 75% of Australian soils contain less than 1% organic carbon in their surface horizons. Obviously the major changes in vegetation cover from forest and woodland to intensive pasture land have had major impacts on both soil fauna and flora and the paths and rates of organic matter turnover in many soils.

Of considerable significance to the development of sustainable agricultural systems is the fact that soil organic matter contains much of the soil's reserves of nutrients and, in particular, nitrogen. Under natural conditions soil organic matter reaches an equilibrium controlled by climate, vegetation and erosion. Clearing, grazing, sowing of introduced species of grass and legume and fertilization upset this natural equilibrium and establish a trend towards a new balance which depends on the nature and magnitude of the changes (Beckwith and Butler 1983).

The degradation of our soil resource is largely associated with the mining and rundown of the native nitrogen and carbon levels in our soils. This loss of nitrogen and carbon bring with it the deterioration of structural stability, as evident in the development of seals, hard setting and easily eroded soil surfaces. Thus the nitrogen and carbon decline in turn exerts influence on the landscape hydrology through changes in soil infiltration and drainage. Under heavy grazing pressure that reduces the soil cover, the work of Bridge *et al.* (1983) demonstrates increased respiration and oxidation of organic matter so to reduce organic matter and the infiltration rate compared to undisturbed pastures. Once the organic matter has been reduced the biological activity (particularly the macropods) in the 'scald' is reduced and this further reduces soil infiltration. The clearing and grazing management can cause substantial changes on soil temperature in the monsoon tropics (Gillard *et al.* 1989). The consequence of higher soil temperatures and drier soil conditions as a consequence of grazing management on the oxidation of organic matter and the population and diversity of soil organisms is largely unknown. It requires our attention. The biological activity of ants, termites, earthworms, and other soil fauna is in many ways a key measure of soil degradation. This area of study is currently neglected, but the work of Holt and Coventry (1988) suggests that grazing management can have extremely important influences on soil biology. The consequences to nutrient and organic matter cycling are unknown but the impact of soil hydrology is most important.

In addition to managing grazing pressure so to maintain soil cover and control soil erosion, we need also to manage the return of organic material to the soil. What level of return of organic material is sufficient to maintain the nutrient and biological condition for soil so that the soil can recover from periods of stress (see Figure 4) is not understood. In terms of sustainable pasture management, answers to these questions are criticial.

Conclusions

To successfully manage the soil resource for sustainable grazing it is essential that we consider the issues in the context of the agro-ecosystem. The fluxes of nutrient and organic matter into and out of the system must balance or be positive in a non-degrading system. There needs to be rapid cycling of this organic matter and nutrient between the soil, the plant and the animal within the system. The organic matter and nutrient condition of the soil is dependent on this cycling. There is a need to see grazing pressure as the management tool not only for soil cover, roughness and erosion control but as a key to management of the organic matter and nutrient condition of the soil. The development of scalds and crusts are testimony to the fact that organic matter bonds and bridges for soil aggregation have been destroyed and with them the soil biological activity. What follows is reduced infiltration, increased erosion and therefore the continuing decline in soil condition.

It is reasonable to expect a sustainable grazing system to show fluctuations in soil conditions but the fluctuations need to be maintained within the limits that allow recovery in times of reduced stress. There is some evidence (De Corte *et al.* 1991), that this recovery is not taking place under current management of native pastures in our tropical rangelands.

The water balance in the monsoon tropics is conducive to significant deep drainage and leaching. It follows that both salinity and soil acidification are soil resource management issues that must receive attention in the Australian tropics. The use of tropical legumes, the clearing of woodlands and the use of introduced grasses are all managements that can radically alter the flux of water, nutrient and salt in the soil profile. The management of these factors is the key to the control of both salinity and soil acidification. In both issues the place and balance of the grass, legume, shrub and tree is fundamental. It calls therefore for careful attention to these soil processes in the development of future pasture technology for the tropical rangelands of Australia. We must look to the whole functioning of the ecosystem and be certain that our striving for short term productivity is not at the expense of long term sustainability.

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