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IMPACT OF SOIL EROSION ON AUSTRALIA'S RANGELANDS

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ABSTRACT

Soil erosion is a natural process which can be intensified by grazing, leading to substantial losses in pastoral productivity. It affects plant growth through reductions in soil moisture and nutrient availability, initial plant community condition prior to rainfall pulses, and changes in species. Erosion may involve both loss and redistribution of soil. Erosion patterns include grazing gradients, hillslope-stream network structures and erosion cell mosaics. Relict erosion patterns resulting from superfloods may also be present. The location and intensity of erosion varies with climate. Hillslopes are often more active during droughts while valley floors and channels are scoured in wet periods. Erosion assessment techniques need improvement if the "convenient myths" which allow people to ignore land degradation are to be laid to rest. There are four ways of dealing with erosion: information, education, legislation and risk management techniques.

INTRODUCTION

Soil erosion involves the detachment of particles or aggregates from the soil surface, their transport by wind or water, and their deposition at some other location either within or outside the property or drainage basin. This is a natural process which has varied through time, even under natural conditions, but it can also be greatly enhanced by the grazing and trampling activities of stock. For example, studies of erosion rates near Broken Hill (1) indicate that the average sediment yield for the period 3000 BP - 1859 AD was 0.037 m^3/ha/yr but after European settlement, the introduction of pastoralism and the rabbit, it increased by a factor of 50.

The factors which lead to soil erosion can produce other forms of land degradation. Erosion is therefore often associated with soil compaction, loss of nutrients, build-up of toxic minerals, increased runoff, diminished plant growth and an increase in the proportion of unpalatable species. This makes it preferable to assess the effects of land degradation as a whole rather than to try and isolate individual processes such as soil erosion.

The costs of land degradation are significant as studies of the mulga lands of southwest Queensland have shown (2). This area suffers from soil loss, nutrient loss, increased runoff and the encroachment of woody weeds. Thirty per cent of the country is eroded and has experienced a loss in pasture productivity of 84%. Twenty per cent of the area has a canopy cover of more than 10% of woody weeds and here pasture productivity has declined by 64%. The value of lost production of meat and fibre could be as high as $32 million which is about 1/3 of the present total.

This paper presents an overview of soil erosion in the rangelands. It deals with effects on plants, types of erosion pattern, including both active and relict ones, and the episodic and spatially variable nature of the process. Some comments are also offered on problems of erosion assessment and how erosion might be dealt with.

THE IMPACT OF SOIL EROSION

In the arid and semi-arid rangeland, plant growth is intermittent and occurs in a pulse after each rainfall. Soil erosion affects the magnitude and shape of these pulses, and through them, the supply of forage. Three separate, but often related effects on the vegetation pulses can be identified: *the soil moisture/nutrient limitation effect; the initial condition effect; and the plant composition effect.*

The *soil moisture/nutrient limitation effect* occurs because eroded areas have a lower infiltration rate and smaller moisture storage capacity leading to greater runoff than stable or depositional areas (2). Furthermore, eroded soils usually have a lower nutrient content than stable or depositional areas because organic material and fines (with sediment-bound nutrients) are preferentially transported (3). The result is that when a vegetation pulse occurs in response to a given rainfall, it will be smaller in eroded landscapes than that of a stable area and larger where there is deposition (Fig. 1a).

The *initial condition effect* occurs when plant response is a function of the state of the plant community immediately before rainfall. Where the community is dominated by ephemerals, plant response to rainfall is dependant on growth from seed stocks. In eroded areas, these stocks may be small because of limited growth response in previous events or because seeds have been transported elsewhere. The subsequent vegetation pulse will therefore be smaller than in stable or depositional areas (Fig. 1b). A similar effect can occur with perennials because fewer survive in eroded areas than in stable or depositional sites and the total number of plants may be smaller anyway.

The *plant composition effect* may be a result of erosion or it may occur when species change has resulted from some other factor. It arises because the shape and magnitude of the vegetation pulse varies with vegetation type and the proportion of ephemerals, perennials and tree/shrub species which make up the community (Fig. 1c). In general, the largest and most rapid response to smaller rainfalls comes from communities with a large number of perennial grasses. Where ephemerals dominate, and plants must grow from seed, there may be no response at all. As rainfall becomes larger, perennial grasses still have the fastest response but differences in the amount of biomass produced become less. Where tree/shrub species dominate, the vegetation pulse may be smaller and much slower than with either ephemerals or perennials. The relationships between plant cover and composition and erosion and deposition are complex (Friedel and Pickup, this volume). For example, in some areas of central Australia, eroded areas are dominated by unpalatable perennial chenopods which produce relatively small increases in biomass in response to rainfall. Perennial grasses are more common in depositional areas and tend to produce much larger increases in biomass after rain although this response may be damped if there is a substantial tree/shrub cover which is often the case.

SOIL REDISTRIBUTION AND RECOVERY

Soil erosion does not occur uniformly across an area, especially at the paddock scale. Instead, a complex spatial pattern results, some areas losing soil, others gaining the eroded material, and other showing no activity at all. The extent to which soil is lost to the system or merely redistributed within a paddock, coupled with associated changes in runoff/runon patterns can be an important determinant of future biological productivity. Loss of soil is greatest where there is a well-developed drainage network. Erosion also usually involves increased runoff so plant production is reduced by both water and nutrient losses. Redistribution involves changes in the relative proportions of eroding and depositional country (4) and is the dominant process in flat areas with distributary drainage systems and erosion cell mosaics. Normally, as erosion intensifies, the size of the eroded area increases more rapidly than that of the associated depositional area where sediment is progressively buried. Forage production is then reduced by a

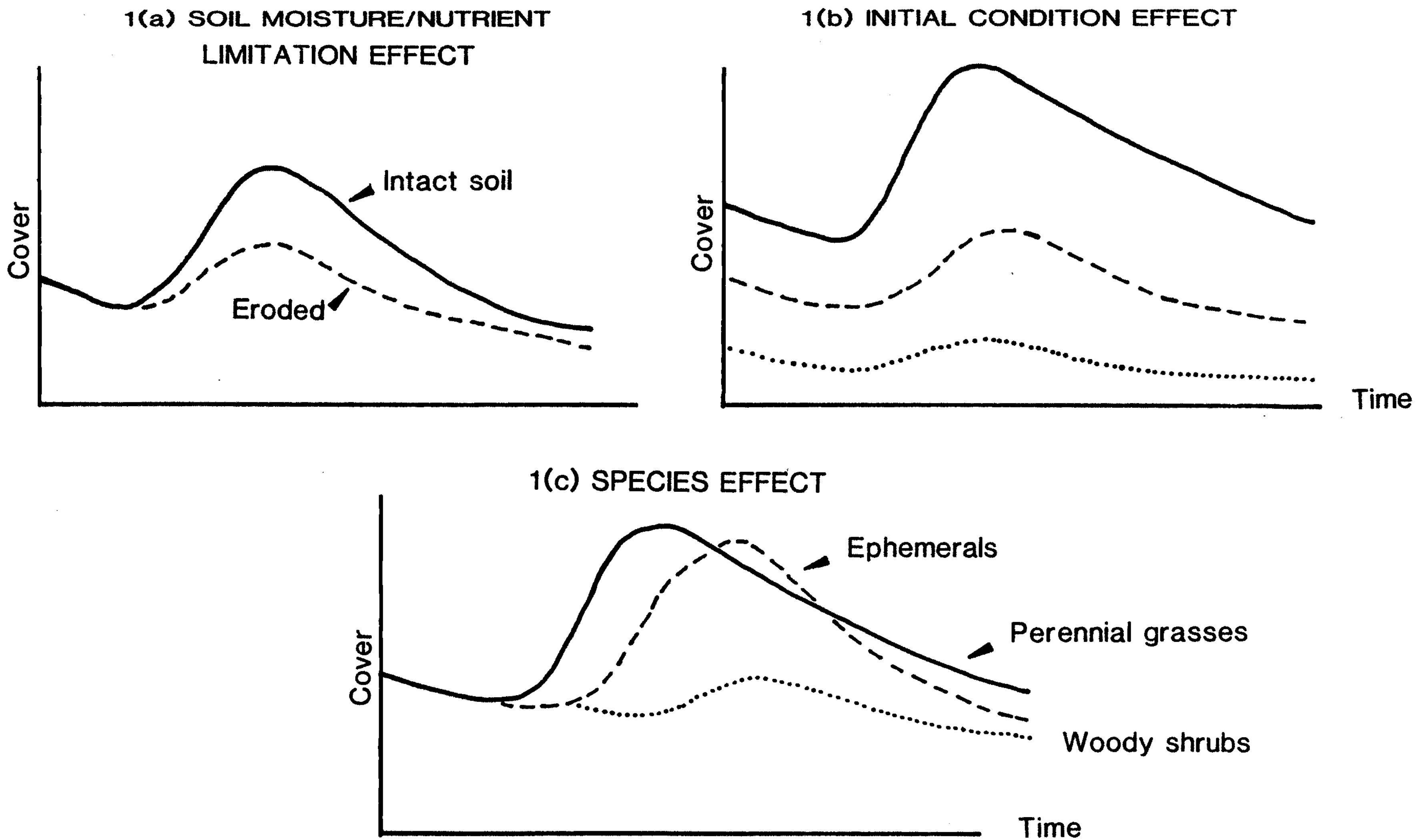

Figure 1: Effects of erosion on plant behaviour.

decline in total plant production as well as adverse species changes in both eroded and depositional areas.

Removal of soil by erosion can have severe consequences for future productivity. Some of the most vulnerable soils in the rangelands consist of thin clay-loan or sandy loam veneers of aeolian or fluvial origin over ancient clay sub-soils. Much of the plant-available moisture and the nutrients are held in the veneers which are not being replenished under current geomorphic processes. Once they are gone, there is little potential for recovery except, perhaps, during "superfloods" (see below). Information on the amount of soil loss and soil redistribution is therefore vital in assessing the resilience of different parts of the landscape under grazing.

SPATIAL PATTERNS OF SOIL EROSION

Active patterns

Spatial patterns of erosion and deposition have not been studied for long in Australia but three distinct types have been recognised: *the grazing gradient; the hillslope-stream network pattern;* and *the erosion cell mosaic*. These patterns are frequently overlaid to varying degrees producing a set of *composite structures*. We are only now beginning to recognise these structures and to disaggregate them into their component patterns (4, 5), thereby showing how some very complex spatial structures can result when grazing-induced erosion is added to natural patterns in the landscape.

Grazing gradient or piosphere-based erosion patterns are circular or star-shaped and are centred on waterpoints. They occur because the intensity of grazing and trampling increases towards water, reducing vegetation cover and increasing the amount of material detached from the soil surface and available for transport. The simplest grazing gradient involves a gradual decrease in the amount of erosion away from the waterpoint and survives because the factors which govern sediment transport capacity (i.e. the ability of wind or water to move available material) are either uniform across the area, which is unlikely, or well in excess of the sediment supply. The spatial pattern of erosion which then develops is largely a function of the spatial distribution of the factors which determine sediment supply. Circular grazing gradient patterns develop in areas of uniform vegetation. Star-shaped patterns occur where several vegetation types occur and some are more palatable than others. Distinct corridors of activity then develop as animals move between waterpoint and the areas of more palatable vegetation.

Pure grazing gradient erosion patterns are probably more a function of wind than water erosion and so develop on fine-grained soils and in areas where catchment size is relatively small or where local runoff is limited. They are common on gibber plains once the stoney layer is disturbed by trampling and on low tablelands with fine calcareous soils. They are less common in sandy areas where the material is too coarse for extensive wind transport under present levels of vegetation cover. It is then more common to find them overlaid on an erosion cell mosaic or a hillslope-stream network erosion pattern. Where this is the case, the grazing gradient may intensify the natural pattern of erosion and deposition, making it very difficult to say what erosion is due to stock and what is natural without computer-based procedures such as those of (5).

Hillslope-stream network erosion/deposition patterns occur in the steeper parts of Australia's rangelands. They develop where there is a well-established tributary draining network fed by runoff and sediment from hillslopes and have been studied in more detail than any other spatial pattern (e.g. 6, 7). The spatial distribution of erosion and deposition in these patterns depends on the relationship between sediment transport capacity and sediment supply, both of which are related to topography. Sediment transport capacity is a function of slope and the amount of runoff which is determined by drainage area. Sediment supply consists of the material already eroded from upstream (and hence, a function of sediment transport capacity) plus the material available for transport locally. In some parts of the drainage basin, transport capacity exceeds supply producing erosion, while in other parts, supply is greater than transport capacity and deposition results. The precise location of erosion and deposition depends on many factors including two-dimensional slope convexity or concavity, the shape of the relationship between runoff and sediment transport (which can vary with slope and sediment particle size, for example), the infiltration rate and the distribution of vegetation cover (7). This produces a myriad of possibilities made even more complex by the fact that erosion may involve sheetflow, rilling or gullying, each of which produces a different sediment transport rate for a given set of runoff, slope and sediment conditions (8). It is therefore normal to treat hillslopes and channel systems separately when modelling hillslope-stream network systems even though the two are coupled.

In spite of the complexity, there are some common patterns of erosion and deposition. Erosion on hillslopes tends to increase from upper to middle sections, reaching a maximum once rills become well-developed. As slope decreases in lower, convex sections, erosion may give way to deposition. This pattern may weaken, intensify or shift up or downslope depending on the rainfall event or the amount of vegetation cover present. In rangelands, where both vary, hillslope erosion can therefore be expected to be a highly erratic process. Sediment from hillslopes accumulates in valley bottoms which often have wide shallow channels characterised by low flow velocities. Where valleys are steeper or small catchments drain into a larger river, valley floors may act as transfer zones rather than sinks so channel systems are better developed (9). Erosion may occur at any location on the channel system depending on the relationship between transport capacity and sediment supply. It may also shift both upstream or downstream over time. In an expanding drainage network, activity is concentrated at the advancing stream head and along the higher order streams with deposition lower down choking channels and causing overbank flooding. Erosion in middle reaches may produce continuous scour and channel expansion but more frequently, it is expressed as a series of waves of alternating erosion and deposition as slugs of sediment are gradually shifted downstream by intermittent and short-lived floods.

Erosion cell mosaics probably cover a larger proportion of the rangelands than hillslope-stream network patterns although it is sometimes difficult to determine a cutoff point between them because one merges into the other. Erosion cells develop on flat arid lands with distributary drainage system sand where the dominant process is sheetflow. In the hillslope-stream network pattern, the major determinant of erosion and deposition is slope. In the erosion cell mosaic, the effects of slope are minor and the pattern of erosion and deposition is more a function of the amount of vegetation present and the strong feedback that exists between soil gain or loss and the ability to produce more vegetation. This means that areas of soil accumulation grow more vegetation which traps more sediment and runoff which further encourages vegetation growth. The processes of erosion and deposition therefore become self-enhancing.

An erosion cell mosaic (10) consists of a set of overlaid and interlocking erosion cells at a variety of spatial scales. Each erosion cell consists of a source zone, a transfer zone and a sink. Source zones actively shed eroded soil, seed and nutrients and are areas of sheetwash, wind erosion, rilling and gullying. Transfer zones occur downslope of source zones and are areas across which soil travels intermittently. There may also be temporary storage of eroded material in localised deposits. Sinks are areas of soil accumulation such as fans, floodouts and floodplains. Erosion cells occur at scales of tens of metres to kilometres and not all of the zones may be present. The configuration of erosion cells may vary. In flat country, cells occur in many shapes and appear randomly distributed. In slightly steeper country, a composite pattern showing some topographic effects may occur, with source zones on slopes and watersheds while the sinks develop along the watercourses and occur as floodplains. The vegetation growth-erosion/deposition feedback is, however, still the main process affecting the spatial distribution pattern.

The development of an erosion cell may involve the removal and deposition of only a few centimetres of soil but this can be sufficient to produce major changes in vegetation. When a grazing gradient pattern is added and the landscape becomes more degraded, erosion cell mosaics intensify. This produces larger erosion cells and a greater proportion of the total area experiencing either severe erosion or deposition (9). The landscape is therefore increasingly partitioned into areas of bare ground and heavily vegetated sink. Also, there will be changes in the response of the landscape to rainfall. Where the erosion cell mosaic is well-developed, the increase in cover after rain will be much more spatially-variable than that occurring in a more stable landscape (4).

While erosion cells develop through the transport and deposition of eroded soil, they also produce changes in the pattern of runoff, infiltration, and runon in the landscape. This involves increased runoff and reduced infiltration in source zones coupled with increased runon in sinks. Where soil degradation rather than soil erosion occurs (e.g. compaction, crusting etc.), features similar to erosion cells may develop from runoff redistribution rather than soil movement. These features are common in mulga lands and occur because reduced ground cover resulting from shrub increase, grazing, trampling, and reduced infiltration capacity due to associated soil structure decline produce higher runoff on slopes and interfluves. The increased runoff means increased moisture supply to shallow washes and creeks where very high densities of woody shrubs develop.

Relict patterns

Not all erosion and deposition in Australia's rangelands is associated with currently active geomorphic processes. Many floodplain and alluvial fan systems show extensive areas of apparent soil loss which are not associated with existing grazing gradients, hillslope-stream network patterns or erosion cell mosaics. There may also be very large depositional structures without any connection to contemporary drainage patterns. The eroded areas are often attributed to high stocking densities in the early days of pastoralism even though they are well away from natural or artificial watering points. The depositional structures are usually explained as relics from past climates yet they show little weathering and obviously post-date major climatic shifts in the Holocene. They can also be an order of magnitude larger than contemporary depositional systems which is too much to be explained by recent climatic change.

Recent studies on the Ross and Todd Rivers in central Australia have shown that some of these erosion and deposition patterns resulted from two enormous floods which probably occurred during the last 2,000 years (11). These floods probably stripped sediment from hillslopes and mountain valleys and deposited a number of large sand threads often in the form of sequences of huge bedforms in narrow ribbons out from the mountain ranges. These threads now provide some of the most productive pastoral country in the area. At the edges of the sand threads and downstream from them, not as much sediment was available for transport and a series of wide, shallow channels were cut. These channels often contain sets of giant ripples up to 100 m across with what are now scalded surfaces between them. Many of the modern erosion cell mosaics occur within these channel systems.

It is highly likely that these "superfloods" play a major role in soil replenishment in areas close to arid zone mountain ranges. Currently active alluvial fans occupy a narrow band at the base of the ranges and there is little evidence of much sediment transport onto the plains beyond that band except on the larger creeks and rivers. The superfloods occupied very large areas and provide the only means by which soil can be transported to and deposited on many areas apart from by wind. After each superflood, these areas became isolated from the main sediment sources in the mountain ranges and a process of local sediment redistribution in erosion cell mosaics becomes dominant where sediment movement does occur. Where local runoff is insufficient to allow redistribution, the area effectively becomes inert although there may be loss of finer sediment through wind erosion, particularly if a grazing gradient develops.

SOIL EROSION THROUGH TIME

Many studies have shown that erosion varies inversely with vegetation cover but at an exponential rate. A small reduction in cover may therefore produce a substantial increase in the rate of soil loss (8). This means that erosion rates tend to be highest during dry times when cover is at its lowest. The reduction in cover also increases runoff so even though there is less rainfall, sediment yield remains high. For example, studies carried out for a dam on the Todd River indicate that total sediment discharge may be ten times higher during a drought than in a wet period.

The effects of pastoral activities on erosion rates is also likely to be at its highest during dry times. In the Alice Springs district, for example, short term climatic variation produces a series of wet periods followed by droughts. Historical evidence shows that cattle numbers begin to increase during major wet periods but reach their maximum during the subsequent dry period (12). Grazing pressure therefore tends to be at its highest when the landscape is in a relatively erosion-prone state.

Erosion rates may not be at their highest everywhere during dry times. There is growing evidence from a number of areas in Australia to suggest that hillslopes and channel systems do not operate synchronously. During dry periods, erosion on hillslopes is at a maximum but flows are not great enough to move the resultant sediment down the channel network which becomes choked (11). In wet periods, hillslopes revegetate,. cutting down sediment supply to channels which are then scoured out by large floods causing channel and drainage net expansion. Alternating wet and dry periods appear to be a normal feature of Australia's climate (13) leading to the suggestion that sediment movement operates like a "jerky conveyor belt" (14) with different parts of the system active at different times.

PROBLEMS OF ASSESSMENT

The complex nature of erosion and the high level of seasonal variability in Australia's rangelands make it genuinely difficult to determine what is going on. In particular, the effects of degradation appear relatively minor when compared with seasonal variability. This has lead to a set of "convenient myths" which allow both the grazing industry and compliant government agencies to avoid accepting that erosion and other forms of land degradation are a problem. They myths include statements like: "The country always comes back", (some of it does but, as a general rule, this statement is quite untrue); "the degradation occurred in the early days when stocking densities were higher", (much of it did but some can be shown to be recent); and, for shrub increase, "the next big drought will thin them out", (it hasn't in areas that have had a shrub problem since the 1900s). If attitudes to land degradation are to be changed, and the problems recognised, the convenient myths must be laid to rest. This will require better methods of assessment and monitoring.

The conventional approach to rangeland degradation is to treat it as a stable system disturbed by grazing. Degradation is then defined as the extent to which present conditions deviate from the stable state. This approach is, at best, a gross oversimplification. Rangeland systems vary extensively in both time and space (5), and for many areas, there is no single condition which represents stability. A better approach is to use the resilience of the system which might possibly be defined as the efficiency with which rainfall is converted into forage over a particular sequence of rainfall events. Degradation then becomes a loss of resilience. It is also better to define resilience in terms of a frequency distribution of responses to rainfall for an area such as a paddock or property to allow for the spatial variability inherent in rangelands (5, 15). Ground and satellite-based degradation assessment techniques which fulfil these criteria are available already (*) or are under development (*).

The techniques for measuring degradation are also deficient. For example, a key problem is to separate human-induced change from natural spatial and temporal variability in the environment. The usual way of making this separation is to identify benchmarks, attributes, sites or areas which have not been adversely-affected by activities such as grazing, assume that they represent "natural" conditions, and then compare them with conditions in supposedly degraded areas. These benchmarks are often selected in a crude and arbitrary manner with disastrous results. Examples known to the author include: the assumption that gullies always result from human activity, selection of "excellent" range condition sites without reference to local runoff/runon conditions, and the placement of exclosures without reference to the distribution of grazing activities. There are also problems associated with the use of point sampling schemes. Virtually all degradation assessment methods measure attributes at a few locations and assume that their results are representative of larger areas. This is frequently not the case (4) and the problems of spatial variability need to be treated much more seriously.

Many of the limitations imposed by conventional land degradation assessment methods can be avoided by combining ground surveys with multi-temporal remote sensing. It is increasingly evident that simple spatial and temporal models of vegetation cover dynamics can be used with remotely-sensed data to extract degradation signatures, to distinguish human-induced change from natural variability, and to remove the effects of season (5, 16, 17). Monitoring agencies have responded poorly to these new approaches, sometimes through inertia, sometimes because they are seen as a threat to existing procedures, and sometimes because they fear the results.

DEALING WITH SOIL EROSION

Few pastoralists deliberately stock at levels likely to produce soil erosion. Most of them also realise that land degradation, in general, and soil erosion, in particular, reduce productivity and are expensive and sometimes impossible to reverse. Why then is degradation so widespread and why does it continue to occur?

In the author's experience, there are three main answers to these questions. First, there is ignorance. Some graziers simply do not realise that they are carrying too many stock at particular times in particular areas. Convincing these individuals that their stock are having an adverse effect is particularly difficult because seasonal changes produce large and rapid shifts in the amount of vegetation disguising the slow underlying trends associated with degradation. Some of them also do not want to know and take refuge in the convenient myths described above. A second cause of degradation can be financial pressure. Some properties may be too small or have debts which are too large to reduce stocking densities. While these properties may continue to operate in the short term, they are not biologically or financially sustainable in the long term without changes in management procedures and some may not be sustainable at all. There are also situations where managers realise the problems of land degradation but are prevented from addressing them by absentee owners demanding a financial return on their investment. A third reason for degradation occurs because pastoralism is a risky business with uncertain rainfall and market conditions and mistakes about stocking pressure are almost inevitable. Degradation risk also varies quite substantially within a paddock because neither grazing pressure nor susceptibility to degradation are spatially uniform. It is therefore quite possible to undergraze some parts of a paddock while overgrazing others. To deal with these issues, we have four main tools:- information, education, legislation and risk management techniques.

Good information on the state of the landscape at regular intervals is a key element in judging the performance of different stocking and management procedures. At the property level, exclosures and fixed photopoints will show a manager how the landscape changes over time and are far better than relying on memory. At the government level, agencies should have a responsibility to monitor the state of leasehold land using ground-based networks or the new satellite-based remote sensing techniques. Whatever the procedure, a baseline needs to be established and techniques used which are capable of filtering out true degradation from seasonal and other types of short term variability. Once this information is collected and reliable methods of assessment are established, there are strong arguments for making it publicly available, particularly where leasehold tenure is involved. At present, government organisations tend to keep their monitoring information confidential and, in cases known to the author, have quietly shelved reports which contained unpalatable conclusions. Reduced information flow is not conducive to the development of sustainable pastoral management and agencies responsible for it are not helping their pastoral clients in the long term.

Effective education programs should raise community awareness of land degradation, should equip pastoral managers with tools to reduce degradation risk in their operations, and should provide a cadre of trained advisers in the extension agencies. These programs should also be aimed at changing attitudes and developing a land ethic. Federal and State Landcare programs address these issues and rely, with varying success, on peer pressure and community-based organisations. There are, however, not enough trained advisers to support regional landcare groups and educational institutions do not provide enough short courses to improve the expertise of group members, particularly in rangelands. These institutions are also proving slow in developing courses to retrain advisers and extension officers in new technology and modern methods of dealing with land degradation.

Legislative and regulatory powers to deal with land degradation exist in a variety of forms but it is rare to see them invoked for a number of reasons. First, because of the complex technical issues involved, cases may be difficult to prove so agencies are reluctant to launch prosecutions. Second, there is an aversion to the "big stick" approach among government agencies partly because of the controversy it would generate but also because it might compromise the "gentle persuasion" approach those agencies prefer. The use of legislative and regulatory powers should continue to be a last resort but these powers will not act as a deterrent unless they are occasionally invoked. It may therefore be appropriate for land management agencies to adopt a more aggressive approach in extreme cases where there is clear mistreatment of the land.

Risk management techniques involve the use of paddock layouts and stock management techniques which reduce the risk of land degradation to an acceptable level. At the design stage, these techniques may be incorporated into property plans and include land capability studies, erosion risk assessment, and waterpoint siting to produce a more even grazing distribution. At the operational level, risk management can include techniques such as the maintenance of minimum acceptable levels of vegetation cover, spelling and stock buying and selling strategies during and after drought. Many of these technical fixes have been developed already. Others are at the post-research stage and require operational testing. All need to be more aggressively marketed and adopted more widely.

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