The dynamics of soil quality in livestock grazing systems

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Abstract

The concept of soil quality integrates physical, chemical and biological properties of soil for a specific land use. Soil structure is nominated as a key soil property because of its critical role in soil water dynamics, plant growth and development, and the suitability of habitat for soil biota. Soil structure dynamics therefore influence agricultural productivity and environmental impact at the catchment scale, and vice versa. In regard to livestock grazing systems, the presence of livestock creates compaction stress, alters the amount of ground cover, and may alter plant productivity, botanical composition and cycling of organic matter, which often alter the form and continuity of soil macropores. In well-managed pastures, these impacts are likely to be moderated by vigorous ground cover, but during climatic extremes such as drought or high rainfall, impacts on soil structural form are likely to be significant and rapid. Large areas of the Australian agricultural landscape are used for livestock grazing, and given that it is not possible or desirable to remove livestock from the ecosystem, we must consider alternative grazing tactics to better manage potential impacts. This paper reviews the concept of soil quality as it relates to livestock grazing systems, and attempts to quantify change in soil quality under specific grazing management, with particular emphasis on soil structure. Recent experimental data derived from image analysis of intact soil cores indicates that rotational grazing management can create significantly larger soil macroporosities compared to set stocked grazing, and that these differences penetrate at least 100 mm below the soil surface.

Key Words

Rotational grazing, soil structure, soil quality, image analysis.

Introduction

A universally accepted definition of soil quality remains elusive, but it is generally accepted that it relates to the functional roles of soil in the landscape (Carter 1996); i.e. as a medium for the physical, chemical and biological processes that support plant growth; in partitioning water flow through the landscape; and as a buffer for environmental change (National Research Council 1993). Consequently, the concept of soil quality includes physical, chemical and biological elements and their interdependence. Although there is disagreement about the scientific rigour associated with this concept and its application (Sojka and Upchurch 1999), and difficulty in applying a generic scheme at various scales of application (catchment, farm, paddock, etc.), it remains a useful platform or framework to investigate soil management options, partly because it is the interdependence of the elements that determines optimum soil management strategies. Soil resilience, defined as the capacity of a soil to recover its functional and structural integrity after a disturbance (Kay 1990; Seybold *et al.* 1999), is a related concept. Resilient soils may better tolerate detrimental management practices, provided a recovery phase or intervention is available.

There have been several attempts at quantifying a soil quality index to enable numerical scoring, which appears to hold value for policy makers, mapping applications and trend analysis at the catchment scale. For land managers, a soil quality approach is most useful if soil quality criteria are linked to soil type, land use and land capability. In this way, key performance indicators of condition and trend can be identified and monitored, and threshold values of ‘good’ or ‘bad’ can be nominated in conjunction with the particular needs and capabilities of the user (for example, Ridley *et al.* 2003, and the Report Card approach suggested by Walker *et al.* 1996).

In this paper, soil structure is nominated as a key indicator of soil quality. Soil structure determines the partitioning of rainfall at the soil surface between runoff and infiltration, and the transmission of water through the profile, which in turn determines the amount of water available to plants and strongly influences the amount of soil lost to erosion. Soil structure also affects plant root growth and development, the cycling of carbon and nutrients, the exchange of gasses in the root zone, the physical

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habitat for soil biota, and the energy required for root penetration and ground engaging tools (Cass *et al.* 1996; Chan and Pratley 1998). At the catchment scale, changes to surface hydrology are likely to be associated with increased erosion and declining catchment health. At the paddock or enterprise scale, reduced plant available water and increased management inputs associated with declining soil structure reduces profitability and sustainability (Chan and Pratley 1998).

Common indicators of soil physical quality include surface infiltration rate, saturated and unsaturated hydraulic conductivity, water holding capacity, drainage condition, aggregate stability, bulk density, soil strength, soil consistence and penetration resistance, used in conjunction with measures of soil carbon content, exchangeable sodium percentage and soil texture. Each has its limitations and advantages. Direct measurement of soil structural form is possible by a number of techniques, including image analysis. Field assessment of soil quality attributes using visual and tactile methods are gaining popularity due to ease of use and reduced monitoring costs, provided some rigour is applied to these observations; for example, the SOILpak series, including Anderson *et al.* (1999). As with any suite of indicators, care must be exercised in regard to validity, reliability and repeatability, and issues relating to spatial and temporal sampling need to be resolved. For example, measures of soil total carbon are often reported, but it is apparent that total carbon is an inadequate measure to predict soil physical properties on its own and that some knowledge of the soil carbon fractions is required (Skjemstad *et al.* 1998).

Within the soil matrix, the distribution, shape and connectivity of pores (i.e. the soil's structural form) are important. For example, in studies of soil hydraulic properties in certain cropping systems, Packer *et al.* (1992) and Murphy *et al.* (1993) have shown that an average minimum macropore diameter of 0.75 mm is necessary to result in significantly different infiltration and runoff characteristics, although the presence of pasture roots is likely to influence the threshold value in a grazing system. Smaller pore sizes are important for microorganisms (1–6 µm) to provide accessible, habitable and protective pore spaces and the biotic interactions this facilitates (van Veen and Heijnen 1994)

Soil structure degradation has been observed since shortly after the introduction of agriculture to the Australian landscape, and has been described as one of the most serious forms of land degradation (Chan and Pratley 1998). Cultivation associated with crop and pasture establishment is a common cause of soil structure decline, but the impacts of livestock are also relevant. Reviews by Packer (1988) and Greenwood and McKenzie (2001) describe many of the potential impacts of livestock grazing on soil quality. Livestock are a major component of farming systems across much of Australia, including high rainfall zones, Tableland zones with steeper topography and limited opportunities for crop enterprises, and mixed farming zones where livestock co-exist with cropping enterprises. It is not possible to remove all livestock from the landscape, so management strategies need to be evaluated in the knowledge that impacts are likely to occur.

Detrimental impacts can be minimised by a number of intervention strategies, including confinement and supplementary feeding of livestock, allocating livestock to sacrificial areas and using amelioration tactics to repair subsequent damage, soil improvement strategies such as drainage of wet areas and pasture improvement, and temporary relocation of livestock to more resilient areas at times when soil or pasture quality may be compromised. This paper suggests that rotational grazing strategies should also be considered, even though the evidence for this has not always been apparent (Greenwood and McKenzie 2001).

Soil quality under pasture

Organic matter

Grace *et al.* (1994) nominate soil organic matter as a precursor to sustainability, with the soil microbial biomass being an important part of the labile pool. In this case, management practices that influence this component become important. Several studies show that soil total C, total N, and microbial biomass C and N, all increase, or at least remain stable, under pasture compared to cropping systems. These trends benefit soil aggregation and stability (Chan and Pratley 1998), as does the removal of tillage during the pasture phase.

The density, activity and subsequent decay of pasture roots provides some resistance to soil structure decline, and opportunity for structural recovery (Greenwood and McKenzie 2001), and the associated microbial activity will encourage greater aggregate stability under pasture compared to cropping systems, particularly where tillage is employed in cropping (Tisdall and Oades 1982). The continuous supply of organic residues, as might be expected from active pasture systems, is necessary to maintain structural integrity in soils where organic matter is the primary stabilising agent (Skjemstad *et al.* 1998).

Pasture botanical composition

Pasture species that possess deep roots of large density probably make a greater contribution to soil organic matter. Mixed-species pastures have been shown to create relatively rapid improvement of soil physical properties such as aggregate stability following a crop phase, with certain grasses described as more efficient in this process than legumes (Harte 2000). The more continuous activity of perennial species is also beneficial. McCallum *et al.* (2004) have shown the potential of perennial pasture species, compared to annual pasture species and crops, to improve macroporosity of a Sodosol through the construction of biopores. Ridley (1996) measured significantly greater hydraulic conductivity under perennial pasture grasses compared to annual grasses, and this was attributed to larger root diameter and density and increased water use. Pastures with a large perennial species composition remain active longer and often use more soil water when it is available, thereby creating potential environmental benefits (Kemp *et al.* 2000).

Pasture productivity

Mele *et al.* (1996) describe a general reduction in pasture productivity associated with a change in botanical composition from native perennial to annual species, brought about by changes in farming systems including grazing management. In south-eastern Australia, this transition has also been associated with degrading soil quality, as indicated by soil acidification, less efficient water use and nutrient limitations (Kemp and Dowling 2000).

Ground cover

A popular standard for minimum ground cover is 75% (Lang (1979), but this relates primarily to protection of soils against erosion. More recently, controlled grazing to retain biomass of between 0.5 and 1.5 t dry matter (DM)/ha, depending on species, have been identified as critical lower levels for survival of perennial species (Kemp *et al.* 2000). Overgrazing inhibits regeneration of roots, soil organic matter and other vegetative productivity.

Soil biota

The abundance, diversity and activity of soil biota can have a direct influence on soil physical properties through incorporation and decomposition of organic matter, production of exudates, which assist binding of soil aggregates and promote burrowing activity (Pankhurst and Lynch 1994). Numerous biological indicators of soil quality have been proposed. In high rainfall areas for example, earthworms are frequently used as a key indicator of soil biological activity in pasture systems. Earthworms can construct macropores and have been associated with increased pasture production (Baker *et al.* 1994). Earthworms are generally more numerous during the pasture phase compared to the crop phase of a rotation Fraser (1994). In drier climates, ants and termites have been associated with improved soil physical quality (Andersen 1990, Lobry de Bruyn 1999).

Impacts of livestock on soil properties

Compaction

Compaction under livestock can be substantial, and this contributes directly to smaller macroporosity, loss of pore continuity, greater bulk density and soil strength (Packer 1988; Greenwood and McKenzie 2001). When soil water contents are large, soil damage associated with pugging and puddling can be expected, particularly when livestock are present and the soil water content exceeds the lower plastic limit (Proffitt *et al.* 1995). Differences in compaction due to stocking rate are difficult to distinguish because it is difficult to separate all the factors that contribute to soil hydraulic behaviour. Reliable reports comparing alternative grazing tactics are rare.

Defoliation and grazing management

Traditional grazing methods such as ‘set stocking’, where a fixed number of livestock are held continuously in each paddock, allow livestock to consume palatable pasture species selectively. Over time, detrimental changes to pasture botanical composition occur, even with conservative stocking intensity. Rotational grazing gives an advantage to the perennial component of the pasture due to breaks between defoliation events, which increase pasture productivity and persistence (Kemp *et al.* 2000).

Excretal return and redistribution

Excretal returns contribute to soil quality and are an integral part of pasture grazing. The grazing and camping behaviour of livestock redistribute nutrients and organic matter contained in both dung and urine (Packer 1988), and low stocking intensities cause greater redistribution because of preferential grazing, walking tracks and camps. The location of watering points, shade, shelter and fences are also factors.

Soil biota

Packer (1988) cites several studies relating grazing intensity to reduction in soil fauna activity, concluding (as does Greenwood and McKenzie 2001) that management practices that influence soil water content, soil temperature and soil organic matter, including grazing practices, influence soil fauna diversity and abundance. Studies on the potential impacts of grazing practice on earthworms, indicate that earthworm density is correlated to pasture production and ‘carrying capacity’ and that this relates to the availability of organic matter under pasture, particularly where clover species increase the availability of nitrogen (Fraser (1994). Fraser (1994) and Baker *et al.* (1994) claim that grazing effects that reduce pasture productivity (e.g. overgrazing, compaction) also influence earthworm density, at least in high-rainfall, improved-pasture systems where earthworms are more common.

Soil resilience and recovery from grazing

Soils high in organic matter, with high aggregate stability and containing a large quantity and density of roots can resist compaction pressures and recover more quickly from them (Greenwood and McKenzie 2001). These conditions are best met with soils under active pasture growth, and prevented from overgrazing.

Effects of alternative grazing tactics

There is little doubt that the presence of livestock can create detrimental impacts on soil quality, but the relative impacts of different grazing tactics are less clear. Greenwood *et al.* (1997) measured significant differences in soil physical properties between grazed (by sheep) and ungrazed pasture plots, as measured by unsaturated hydraulic conductivity, bulk density (0–80 mm) and soil penetration resistance, but found no difference between low, medium and high stocking rates after 30 years of grazing. It was concluded that livestock effects are cumulative over time and that soil physical properties are unaffected by stocking rate in the long term. Though several studies demonstrate that higher stocking rates are detrimental to soil physical properties, they are mostly short duration studies that focus on impacts at large moisture contents. Reviews by Packer (1988) and Greenwood and McKenzie (2001) revealed few studies comparing alternative grazing tactics (for example, comparing set stocked grazing management to various forms of rotational grazing, at equivalent stocking rates), particularly in Australian conditions.

However, the increasing evidence that rotational grazing supports greater persistence and productivity of perennial pastures, and can contribute to beneficial changes in botanical composition, combined with the potential environmental benefits this may bring, leads to speculation that rotational grazing may also benefit soil quality. Given that the presence of livestock on a continuous basis, even at low stocking rates, can reduce soil and pasture quality, grazing tactics need to be designed to minimise detrimental impacts and maximise opportunities for rapid soil/pasture recovery. The rest period associated with rotational grazing appears to be an important component of this recovery.

In a three year replicated experiment comparing set stocking with rotational grazing of sheep and an ungrazed control (experimental set-up described in Southorn (2002)), image analysis techniques proved useful in detecting subtle differences in soil structural form not found by other measures of soil structural condition. Data from this study suggests that under the conditions of this experiment, rotational grazing impacts on soil structural form to a smaller extent than set stocking, and can maintain soil macroporosity to the same extent as soils protected from grazing (Figure 1). For the duration of this experiment, topsoil macroporosity (averaged over 10, 50 and 100 mm sampling depths) decreased to a significantly greater extent after 2 years under set stocked management than it did under rotational grazing. The largest average topsoil macroporosity was consistently measured at locations where pasture was grazed through cages which prevented hoof pressure on the soil surface. The trend under ungrazed soil, where pasture became dominated by large quantities of dead and stalky vegetation, was inconsistent.

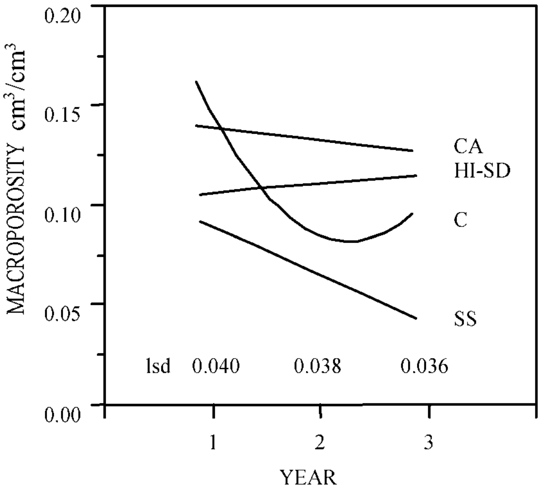

Figure 1. Average topsoil (0-100 mm depth) macroporosity under alternative grazing tactics with sheep over 3 years. Data points not shown for clarity; lines are those of best fit. Least significant difference is within any year at 5% (SS ≡ set stocked, HI-SD ≡ high intensity short duration rotational grazing, C≡ ungrazed control, CA ≡ grazed over pasture cages).

Under the same treatments shown in Figure 1, larger macroporosity was measured not only at the soil surface, but to a depth of at least 100 mm (Figure 2). At this depth, significantly larger macropores were observed under rotational grazing and pasture cages compared to set stocked grazing. This indicates that the mechanisms generating macroporosity operate throughout the potential depth of influence of compaction.

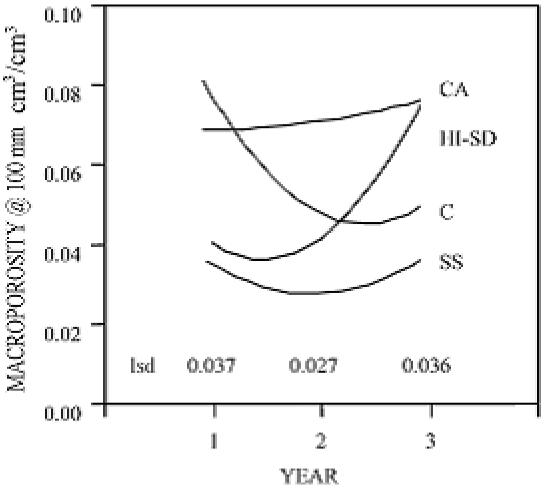

Figure 2. Average soil macroporosity at 100 mm depth under alternative grazing tactics with sheep. Presentation and treatment details as for Figure 1.

The larger macroporosity was likely due to the combined effects of rest from grazing; reduced hoof pressure, reduced defoliation, greater pasture productivity, increased root channel development, and increased soil macroinvertebrate activity. In this experiment, there were no significant differences in soil bulk density (to 50 mm), total organic carbon content, hydraulic conductivity (at 10 mm tension), soil microbial activity or pasture botanical composition, highlighting the greater sensitivity of image analysis to detect subtle differences in soil structural form.

Conclusion

Management strategies that enhance soil organic matter content on a continuous basis contribute to improved soil structure and structural resilience, and contribute to improved soil quality. In the context of livestock grazing systems, maintenance of active pasture growth is critical, not just to soil quality but also to enterprise productivity and environment protection. The presence and persistence of perennial species in the pasture botanical composition is an important part of this strategy, best managed by rotational grazing. The rest period associated with rotational management can assist pastures and soils to recover from the impacts of livestock, provided other conditions are met.

The ‘other’ conditions, however, are often difficult to achieve. Significant soil damage is likely if livestock are present when soil water content is high, regardless of stocking rate or grazing strategy. To protect soil, this requires periodic relocation of livestock, which is not always possible. Grazing management tactics will not eliminate agronomic constraints. Consequently, rotational grazing must be accompanied by intensive management strategies. Subsoil constraints remain problematic, particularly in pastures where treatment options are limited by terrain. Farm layout (fencing, water supply, shade and shelter) may need to accommodate a greater number of smaller paddocks, which obviously reduces the flexibility of mixed enterprises. This investment needs to be assessed in conjunction with the relative returns from livestock and crop enterprises. Grazing tactics used during the pasture phase of a crop-pasture rotation need additional consideration. Flexible grazing strategies that enable rapid adjustment of livestock numbers will be better suited to variable climatic conditions. Regardless of the grazing tactics employed, land managers are encouraged to include soil quality criteria in the monitoring program of farm performance, using a suite of indicators that are relevant and reliable.

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