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ECOLOGICAL IMPLICATIONS OF GRAZING SYSTEMS:

PASTURE MANAGEMENT EFFECTS ON SOIL BIOTA

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Abstract. The many types of organisms in soil form an intricate food-web which governs the decomposition of organic matter, the cycling of nutrients and helps maintain soil structure. Sustainability of the grazing system is dependent on efficient functioning of these biological processes. Pasture management practices such as stocking rate, the use of fertilisers and other agrochemicals, pasture renovation, irrigation and the introduction of exotic soil animals all have effects on the soil biota, some adverse, others stimulatory. Soil acidification, which may be associated with clover dominance, can also affect pasture biota. The effects of management on soil organisms are reviewed in relation to their potential role in sustaining production from the grazing ecosystem.

The maintenance of a healthy and viable population of soil biota is one important aspect of sustainability. Grassland soils teem with organisms whose activities are vital for the maintenance of soil structure, organic matter breakdown and the cycling of mineral nutrients. These biological processes are influenced by the impact of management, some favourably, others adversely. For such practices to be sustainable, the impact should be minimal, or at least, capable of amelioration, so that on-farm soil fertility and the biological processes that mediate it, can be sustained. Increasingly, off-farm effects of farm management practices are being considered as environmentally important; for example, nutrient run-off and water quality. However, this review will be directed at the on-farm effects of management practices on soil and litter biota of pastures and the implications that these practices may have for sustaining the grazing enterprise.

The soil biota

The term, "soil biota", in this review includes not only the community of organisms which live beneath the soil surface, but also those that live in the litter layer and dung overlying soil. Soil organisms are of many and diverse types. Their numbers per unit area are often in inverse proportion to their size, with smaller organisms having a relatively larger metabolism.

The array of soil invertebrates includes insects, arachnids, protozoa, nematodes, earthworms, millipedes, fly larvae, beetle larvae, ants, and other smaller, lesser-known animals. Species diversity in pastures appears to be high. For example, in native and improved pastures at Armidale there are at least 40 species of Collembola alone (King *et al.*, 1976; King, 1989a). Sizes for soil organisms range from lengths of 0.001 mm (bacteria) to over 100 mm (earthworms). The biota are generally divided by size into micro-organisms (bacteria, fungi, actinomycetes and algae), microfauna (protozoa), mesofauna (Collembola, Acari, nematodes) and macrofauna (earthworms, millipedes, larger insects).

High numbers of earthworms (over 400/m^2) have been measured in pastures in Tasmania and SA (Lobry de Bruyn, 1993; Baker *et al.*, 1992). In contrast, the numbers in grazed pastures at Armidale were lower (145/m^2) (Hutchinson and King, 1980). Microarthropods (Collembola and Acari), being only a few mm long, would seem to be insignificant, but they have high metabolic rates and occur in large numbers, from 12,400/m^2 in lightly stocked native pastures to 25,500/m^2 in similarly stocked improved pastures at Armidale (King and Hutchinson, 1976; 1983).

Although the invertebrate animals attract attention through their relatively larger size and high mobility, it is the micro-organisms which are the main agents for decomposition and nutrient cycling in all ecosystems. Numbers of fungi and bacteria are difficult to measure, but they are very high in comparison with the fauna. A more usual measure of their presence is biovolume or biomass. Soil microbial biomass is much larger than previously realised. Sparling *et al.* (1986) obtained an average value of 650 µg carbon per gram of soil in the top 5 cm of 17 New Zealand soils. This translates into around 5,500 kg/ha (equivalent to the mass of about 110 sheep/ha).

Soil biota migrate up and down the litter and soil profile, but most biological activity occurs in the top 10 cm of soil and litter. Some organisms can move relatively quickly (spiders, centipedes) and others move only slowly (micro-organisms). Slowly moving organisms often depend on faster moving animals to transport them. Dung beetles transport mites, and microarthropods re-distribute fungal propagules through the soil on their bodies or in excreta from their guts. The distribution of soil organisms also depends on soil organic matter, which represents their food base and habitat. Moisture, temperature and aeration also determine levels of biological activity in soil.

The functional importance of soil biota is not directly proportional to their biomass. Taking metabolic activity as one measure, Hutchinson and King (1982) partitioned energy usage between various components of the soil biota in intensively grazed (20 DSE/ha) improved pastures at Armidale (Figure 1). Microbial respiration accounted for 70% of the total energy expended on these pastures in one year. In contrast, the sheep flock used 26%, and the invertebrates 4%.

Function of soil organisms in grazing systems

The main roles of soil biota are to sustain soil fertility by decomposing organic residues, release nutrients and contribute to the maintenance of soil structure. The overwhelming majority of organisms that colonise the organic residues from plants and dung from domestic animals are beneficial. Organic residues are fragmented and reduced physically in size by invertebrates, thus increasing the surface area available for microbial colonisation. Lee (1985) found that earthworms processed up to 17% of the total nitrogen in Polish pastures, and brood masses of dung beetles have been shown to be a source of phosphorus for plants (Ridsdill-Smith, 1989). Invertebrate size is no measure of importance since King (1989a,b) found that the presence of microarthropods can increase the transfer rate of P, S and N from pasture litter by 50%, reflecting a remarkable synergism between these fauna and the microbial colonisers of pasture residues. However, it is the micro-organisms that have the central role in nutrient cycling. Mineral nutrients are bound in organic complexes and microbial enzymes can break these bonds, releasing the mineral elements which become available for re-use by plants.

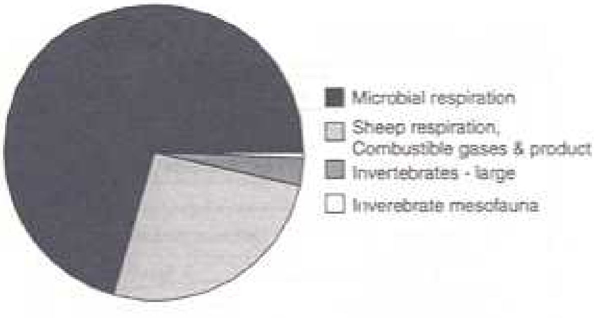

Figure 1. Partitioning of energy use (percent) between different components of the grazing ecosystem (From Hutchinson and King, 1982).

Soil organisms affect soil structure as well. The burrowing activities of the larger invertebrates create macropores which improve aeration and water infiltration. Roots find their way easily down these channels and the animals also mix mineral soil and organic particles. The role of soil microbes in improving soil structure is to secrete biochemical exudates which provide binding agents for stable soil aggregates.

Mangement practices in grazing systems

Stocking rate.

High sheep numbers on improved and native pastures at Armidale reduced the numbers of both large (earthworms, scarab larvae,millipedes) and small (microarthropods, enchytraeids and nematodes) decomposer animals (King and Hutchinson, 1976,1983; Hutchinson and King, 1980). Although Baker *et al.* (1993a) found that increased sheep numbers had no effect on earthworm biomass or numbers on pastures at Hamilton in Victoria, the highly stocked treatments in this work were not as repressive as in the Armidale study. When pastures are overgrazed, the soil becomes compacted with reduced pore spaces, restricting the movement of the non-burrowing soil animals such as Collembola, Acari and nematodes in particular. Soil pore volume of pasture soils decreases with increasing stocking rate of sheep (King and Hutchinson, 1976). This decreases the oxygen levels in the soil and slows water infiltration rates, thus increasing the incidence of surface run-off with consequent erosion and nutrient loss problems.

Overgrazing also removes the litter layer (King and Hutchinson, 1976; 1983; King, 1989a) which has several important consequences. The litter layer acts as a moderator of abiotic conditions in the soil, insulating the soil environment from the effects of hot and cold conditions and slowing evaporation to retain favorable soil moisture conditions. Under high stocking regimes, the main detrital food source changes from litter to dung. The aggregation of dung in sheep camps changes the distribution of the base of the food supply for the whole detrital food web.

Both numbers of and species richness of biota are affected by the intensity of stocking. Numbers of Collembola species declined from 28 to 17 in native pastures and from 21 to 15 in improved pastures as sheep stocking increased from low to high levels (King *et al.*, 1976,1985). Soil microbes can also be affected by stocking rate. Hutchinson and King (1982) found that increasing stocking intensity of sheep from 10 to 30/ha did not alter the soil microbial activity overall, but higher microbial respiration occurred in sheep camps where organic matter of soil was higher, due to the aggregation of excreta. For plant residues, fungi predominate as the colonisers (Hutchinson and King, 1989) and the removal of sheep from pastures has been associated with an increase in the total hyphal lengths in the surface soil (Bardgett, 1991).

There has been no work done comparing the effects of rotational grazing *versus* set stocking on soil biota. However, there have been claims that the former is advantageous. These claims await substantiation.

Superphosphate and sown pasture species

Australian soils are low in phosphorus (P), sulphur (S) and nitrogen (N). Temperate pasture improvement in Australia has been based mainly on superphosphate, which contains P and S, and on N fixed by legumes. The final component of improvement has been the introduction of productive and nutritious grasses that respond to the improvement in fertility. Total annual P uptake by plants, above and below the ground, can show a tenfold increase due to pasture improvement (Hutchinson, 1989) and this flows on to the organic side of the nutrient cycle (Figure 2). Budgets for S and N are expected to be similar, although the more mobile sulphate and nitrate ions will be less well retained.

There is a pervasive community view that there are deleterious effects of inorganic fertilisers on soil biota. In forest soils, there were early reports of short-term reductions in microarthropod numbers which were thought to be due to an increase in osmotic potential due to a rise in salt concentration in the soil solution (Huhta *et al.*, 1967; Lohm *et al.*, 1977). However, Marshall (1977) reviewed early studies and concluded that there was a general increase in numbers and species of soil fauna following the application of inorganic fertilisers and this effect was most probably a result of increased primary productivity and herbage quality. Marshall's conclusion has been extended by a number of studies based on differences between sown, fertilised pastures *versus* native species in natural, unfertilised pastures at Armidale, NSW.

Numbers of useful invertebrate fauna increased with pasture improvement based on the use of superphosphate and sown species (King and Hutchinson, 1983; King, 1989a). Baker *et al.* (1993a) found little difference in earthworm numbers and biomass between phosphate treatments in Victorian pastures at Hamilton. However, stocking rates increased with P levels in this trial and this may have diminished the earthworm response. Microarthropods can be particularly responsive to pasture improvement, with Collembola numbers on improved pasture sites being three times higher (46,000/m^2) than on native sites (14,500/m^2). For Acari, the difference was 1.5 times (25,100/m^2 *vs* 17,100/m^2) (King and Hutchinson, 1976,1983). With pasture improvement, the native Collembola tend to be replaced, but not eliminated, by cosmopolitan, introduced species (King *et al.*, 1976; 1985; King, 1989a). The soil microbes that colonise litter from sown species in improved pastures have higher respiration rates and biovolumes than organisms colonising native species from natural, unfertilised pastures. These microbial parameters are strongly correlated with litter decomposition rates (Hutchinson and King, 1989).

Dry matter decomposition and the transfer rates of P, S and N from sheep dung to soil are faster in dung from sheep grazing improved pastures than in sheep dung from native pastures (King, 1993), probably due to differences in microbial volume and respiration activity. The presence of larger numbers of Collembola and Acari in sown, fertilised pasture substantially increases the transfer rates of P, S and N from litter to soil (King, 1989a; 1989b; King and Hutchinson, 1992). This provides a clear example of the importance of invertebrate/microbial synergisms and the value of maintaining a high level of biotic activity to promote the cycling of nutrients.

Soil pH and liming

Lime is generally applied to pastures to improve

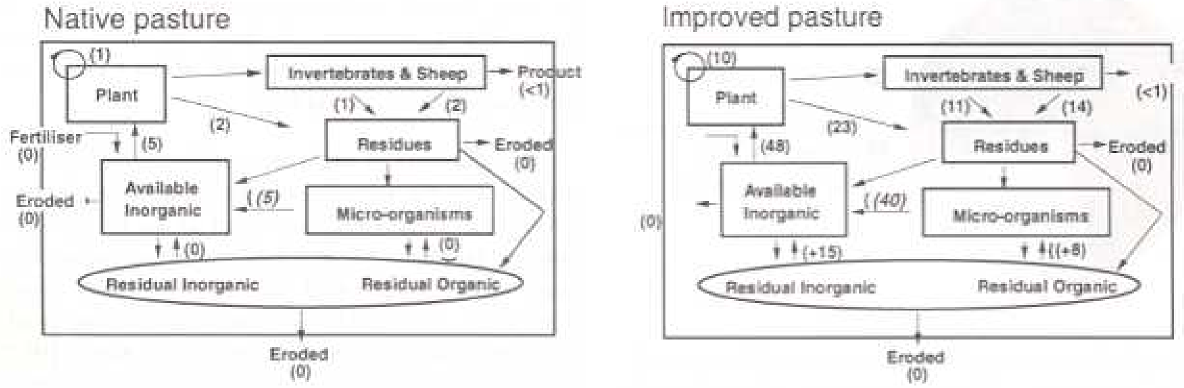

Figure 2. Annual P budgets (kg/ha) for both native and improved pastures at Armidale, NSW. (From Hutchinson, 1989).

the structure of clay soils and to ameliorate acid soils. The application of lime to pastures at Hamilton in Victoria had no overall effect on earthworm numbers (Baker, 1992). However, species reacted differently, with some increasing in abundance while others declined. Liming can change the relative proportions of fungi and bacteria, increasing the total bacterial numbers and decreasing fungal numbers (Alexander, 1961). However, Shah *et al.* (1990) reported that the large increase in bacterial populations immediately following liming upland pasture did not persist and there were no changes in total fungal populations.

King and Hutchinson (1989) derived a relationship between microarthropod numbers and pH based on long-term data on Rothamsted pasture plots (Edwards and Lofty, 1975). An optimum pH for both Collembola and Acari occurred at pH 6.0, but numbers were lowered by about 75 per cent when pH fell to 4.5. Effects of pH may be direct or indirect by affecting the microbial food supply. Long-term acidification of soils can occur under legumes, with a decline in pH of 1 unit in 50 years being widespread for pastures (Pearson and Ison, 1987). Acid soils under improved pastures may alter the size and composition of assemblages of biota involved in nutrient cycling. The potential for introduced earthworms to mix surface-applied lime through the soil profile will be discussed under "Introduced Biota".

Ecotoxicity of antiparasitic drugs

Some drugs used to control helminth and arthropod parasites of domestic livestock can have ecotoxic effects, particularly on dung fauna. Ivermectin, dichlorvos and phenothiazine are notable in this respect (Blume *et al.*, 1976; Lumaret, 1986; Madsen *et al.*, 1988). Most ecotoxicological studies on antiparasitic drugs have been done on the avermectins, a new family of drugs released onto the Australian market in the 1980's with a broad spectrum of action effective against both intestinal nematode parasites and ectoparasitic arthropods. Most of the avermectins pass from the animal in the faeces, whatever the route of dosage. Disappearance of the drug from the faeces varies from 6 days or less (Lumaret *et al.*, 1993) to more than 45 days (Sommer *et al.*, 1992). Strong (1992) has reviewed the effects of the avermectins on insects in cattle dung where they were shown to reduce the larval survival of dung-breeding Diptera and dung-beetles. Similar effects have been found for sheep dung (Wardhaugh *et al.*, 1993; Mahon *et al.*, 1993). Wall and Strong (1987) and Madsen *et al.* (1990) reported that the disappearance of cattle dung was delayed in pats which contained avermectin. The latter had fewer arthropods but there was little effect of the drug on earthworms. Barth *et al.* (1993) found that, although dung containing ivermectin had fewer Coleoptera and Diptera larvae and dung-specific nematodes, the overall degradation of dung was not significantly lowered. Little is known of the effects on the smaller decomposer invertebrates such as microarthropods, free-living nematodes and soil microbes which are also very important in the breakdown of the dung pat. However, Onishi and Miller (1985) found no effects of avermectin on fungal activity.

Despite the adverse effects of avermectin on the fauna which arrive first at the dung pat, the overall effect of the drug on the rate of decomposition and nutrient cycling in pastures grazed by sheep over the course of an entire year may be small. Calculations for phosphorus budgets on both native and improved pastures indicate that the amount of phosphorus recycled in these systems may be reduced by only 5% at the dosage levels currently recommended for the drug (King, 1993).

Moxydectin, a macrocyclic lactone like the avermectins, is new to the market in Australia and seems to have less adverse effects on the dung fauna than the avermectins, but few studies have been conducted on this product. Doherty *et al.* (1994) found that moxydectin had little effect on dung-beetles and buffalo fly larvae in cattle dung. The drug also appears to have no effect on bush fly larvae (Wardhaugh *et al.* pers. comm.).

Effect of herbicides on soil biota

Herbicides make up 44% of the world market for non-fertiliser agrochemicals and are the fastest growing sector of this market (Evans and Finney, 1992). In pastures, glyphosate, simazine, 2,4-D, paraquat, diquat, MCPA and metsulfuron are commonly used in renovation and spray-topping pastures. Many fungi and actinomycetes have a high degree of tolerance to herbicides and few herbicides have any great or prolonged adverse effect on the total bacterial component of soils when herbicides are used at normal field rates (Anderson, 1978). However, herbicides can be as selective in their action among micro-organisms as they are with plants (Grossbard, 1976) and some herbicides will affect certain microbial species more than others.

The effects of glyphosate on microflora, including ectomycorrhizal fungi, are neglible (Chakravarty and Chatarpaul, 1990a,b; Schuster and Schroder, 1990; Wardle and Parkinson, 1991). Wardrop (1986) reported that glyphosate did not have much effect on the soil microbes except in stimulating cellulose decomposition. Glyphosate does depress the growth rate of some earthworms (Springett and Gray, 1992). The herbicide 2,4-D would seem to stimulate soil respiration and microbial biomass in the short term, but in field experiments extended over 290 days, Wardle and Parkinson (1991) found no effect of this herbicide, which appears to have little deleterious direct effects on Collembola and Acari numbers (Rapoport and Cangioli, 1963; Fox, 1964; Edwards, 1965; Davies, 1965; Prasse, 1975).

Anderson (1978), in his review on pesticide effects on non-target soil microbes, states that simazine, applied at normal field rates, had no adverse effect on fungi but did stimulate some mycorrhizae. There would appear to be little effect of simazine on earthworms (Lee, 1985) but it reduced numbers of Collembola by 60% when averaged throughout the year following application. However, its effect on Acari was less persistent (Prasse, 1975). Edwards (1965) found that simazine reduced numbers of soil fauna to one-third to one-half compared with those in untreated soil. Collembola, particularly the isotomids, were most affected by simazine, and earthworms, Diptera and Coleoptera larvae also declined in numbers. These reductions in abundance were still apparent for up to four months after application of the herbicide (Edwards, 1965).

Wardrop (1986) states that paraquat had little effect on total populations of soil microbes or enzymic activity although it may delay cellulose decomposition. Earthworms suffer few effects from paraquat (Lee, 1985; Caseley and Eno, 1966). MCPA had no effect on grassland arthropods even after continual annual applications (Davies, 1965; Rapoport and Cangioli, 1963).

Compared with cropping, herbicides are used infrequently on pastures and their effects would appear to be relatively small and non-persistent. New generation herbicides, such as the sulphonyl ureas (*eg.* metsulphuron) are used in low concentrations (less than 10 g ai/ha), which should ensure minimal environmental effects.

Cultivation and pasture establishment

Cultivation of soil, depending on its intensity, may affect the soil biota. The effects will be far greater in cropping soils than in pastures where disturbance is restricted to establishment and renovation. Ploughing and reseeding pasture resulted in a 50% decrease in the numbers of total arthropods, particularly hemiedaphic Collembola, and Cryptostigmatid mites (Edwards and Lofty, 1975). However, earthworm numbers increased over a two year period with cultivation and reseeding (Edwards and Lofty, 1975), which may have been due to the increased supply of organic matter from the incorporated sward (Curry, 1986). Other groups of soil arthropods such as prostigmatid and mesostigmatid Acari and Diplopods were only slightly affected (Edwards and Lofty, 1969). In general, species with a short life cycle repopulated cultivated soil within a single growing season.

Less physically disruptive methods are increasingly used to establish and renovate pastures. The use of herbicides in conjunction with surface seeding or direct drilling should minimise effects of cultivation. The effects of herbicides on soil biota have been dealt with above.

Irrigation and drainage

Summer irrigation changed the proportions of the two main earthworm species inhabiting improved dairy pastures in Tasmania (Lobry de Bruyn, 1993). Following irrigation, numbers of *Aporrectodea caliginosa* declined by over 50 per cent while *Lumbricus rubellus* increased during the two irrigation seasons studied. *L. rubellus* would appear to be less sensitive to trampling associated with irrigation. Conversely, Baker (1992) has shown that drainage increased numbers of earthworms, especially *A. caliginosa*, in pastures at Hamilton, Victoria. Earthworms showed no changes in total abundance with irrigation but different species dominated irrigated and dryland pastures in the Mt Lofty Ranges in South Australia (Baker *et al.*, 1994).

Introduced biota

Dung beetles were introduced into Australian pastoral soils with the CSIRO Dung Beetle Project primarily to control buffalo and bush flies. An added bonus is the quick fragmentation and burial (within hours) of dung in the soil, bringing it into contact with microbes with a subsequent increase in decomposition and release of nutrients to the soil. So far, 17 species have become established in NSW, 4 in Victoria and 4 in Tasmania. However, their natural rate of spread is slow (Creagh, 1993).

Earthworms have been introduced into Australian pastures for a variety of reasons. Those introduced into irrigated pastures at Deniliquin incorporated the accumulated litter mat into soil. Mat weights were reduced from 72 to 8 t/ha when earthworms were present (Noble *et al.*, 1970). Baker *et al.* (1994) have reviewed the requirements for the management of earthworms which may be introduced into pastures to both improve soil structure and fertility, and to bury fertilisers such as lime. Baker *et al.* (1993b) demonstrated that the earthworm *A. trapezoides* was more efficient at burying surface-applied lime in pastures than *A. rosea*. The rate of dispersal of both dung beetles and earthworms has been relatively slow, although there have been more widespread introductions of dung beetles.

Conclusions

Efficient nutrient cycling and the maintenance of good soil structure are two very important aspects of sustaining the biological fertility of grazed pastures. Management practices such as stocking rate, application of superphosphate and the sowing of legumes probably have the most profound and sustained positive effects on soil biota in those areas not subject to irrigation or acidification. Non-fertiliser agrochemicals and cultivation effects would appear to be relatively short lived, as these practices are only used sporadically, and introductions of invertebrates are generally only on a limited scale. Overgrazing with high sheep numbers has not only adverse effects on soil biota, but also on botanical composition of pastures. Fertilisers will maintain the presence of nutritious perennial grasses and legumes and will increase and sustain high levels of soil biological activity provided gross soil dysfunction does not develop. Management for healthy and viable soil biota populations would appear to be compatible with good agronomic practice, and sustained biological fertility of pastures is achievable as long as both objectives are attained.

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