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INFLUENCE OF IMPROVED PASTURES AND GRAZING ANIMALS ON NUTRIENT CYCLING WITHIN NEW ZEALAND SOILS

Summary: The improvement of New Zealands pastures over the last ISO years has increased the nutrient status of the soil as a result of the application of fertiliser, an increased soil organic matter content and increased biological activity. The grazing animal has also influenced the nutrient status of the soil by increasing the rate at which nutrients cycle between the soil, plants and animals. However, the grazing animals also cause losses of nutrients from the soil through concentrating nutrients into small volumes of soil under dung and urine patches, redistributing nutrients around the farm and removal of nutrients in the form of animal products. If these losses are not replaced by fertiliser applications then reductions will occur in both the amount of nutrients in the soil and in pasture production. Research directed toward maximising the cycling of nutrients originating from animal excreta is required in order to develop strategies to minimise fertiliser inputs.

Keywords: Animal excreta; grazing animals; nutrient cycling; pasture; soil fertility; soil organic matter.

Introduction

Today, New Zealand's pastoral industry involves a land area of 14 million ha, the majority of which is improved pasture (New Zealand Agricultural Statistics, 1987). The natural climax vegetation of most of this productive land was forest. Indeed, a thousand years ago indigenous forests covered the majority of New Zealand (Cameron, 1962). The main unforested areas were those where climates were too extreme to allow forests to develop or where volcanic eruptions, floods, earthquakes and fires had created seral conditions (Holloway, 1954).

With time, much of the original vegetation of New Zealand land has been removed and replaced by highly productive pasture plant species. The large differences in climate, topography and soil type which occur within New Zealand have resulted in different types of pastoral farming (e.g., dairying, meat production and a mixture of meat production and cropping) predominating in different localities. Despite this variation, all of these farming systems are based on grass/clover pastures which require topdressing with lime and fertiliser. The combination of improved grass and clover species, topdressing and a generally temperate climate provides an opportunity few other countries have for all-year-round outdoor grazing by stock.

In this paper, the changes in soil properties due to pasture development are outlined and the cycling of nutrients within typical grazed pasture ecosystems in New Zealand are discussed. The dominant role of the grazing herbivore in cycling and loss of nutrients is emphasised.

Soil fertility and pasture development

Over the last ISO years, 9.3 million ha of New Zealand have been developed into improved pastures from forest, fern, scrub and tussock (New Zealand Agricultural Statistics, 1987). The development of these areas involved the removal of the existing vegetation through felling, burning and/or ploughing, then oversowing with introduced pasture plant species. For a while the pastures established by seeding on cleared forest lands were productive and vigorous because of the reserve of fertility remaining from the humus and ash of the forest burn. However, as fertility declined it became more difficult to maintain the sown pasture species in competition with forest regrowth. Sustained heavy grazing pressure was necessary to control the secondary growth and such pressure could only be achieved with adequate subdivision fencing. Highly productive pastures could only be maintained through application of fertiliser and lime to ensure that the soil was adequately supplied with nutrients.

In general, the high-yielding, improved pasture species used have a large demand for soil nutrients, although less fertility demanding legumes (such as *Lotus pendunculatus* Cav.) are sometimes used in pastures on infertile soils. The most commonly used legume is white clover *(Trifolium repens)* which is not normally a pioneer legume but follows early development by other legumes (Sears, 1962). Although many ecotypes with differing nutritional preferences exist (Snaydon, 1962) white clover is generally adapted to high fertility conditions (high available P and Ca and a moderate pH; Levy, 1970). Furthermore, when grown in association with grasses, white clover is generally a poor competitor for P, K and S (Haynes, 1980); thus an adequate supply of these nutrients in the soil is necessary for clover growth. Pasture grasses too are mostly adapted to high fertility conditions. Indeed, few if any of the important cultivated pasture grasses are constituents of the major climax grassland ecosystems of the world. The typical agricultural grass species of *Lolium, Dactylis, Festuca* and *Poa* are allied to, and probably derived from, grasses of woodland and forest margins where rainfall and soil fertility are generally relatively favourable (Tothill, 1978).

Nitrogen is supplied to New Zealand pastures mainly by symbiotic N_2 fixation by the legume component of the pasture. A high level of pasture production is therefore based on the establishment and maintenance of a satisfactory legume content to supply N to the associated pasture species. Despite this the grass component of the pasture is often N deficient (Henzell, 1981) and strategic use of fertiliser N to improve pasture production is sometimes practised. Small amounts of N (25-50 kg N ha^{-1}) are applied in early spring or autumn when legume growth is characteristically weak (O'Connor, 1982).

In order to maintain the highly productive pasture species, particularly clover, in the sward regular fertiliser inputs (especially P and S) are required. Topdressing of pastures began in the 1880s (Smallfield, 1935). Since then there has been a steady increase in the amount of fertiliser applied each year (Figure I) as the area in grassland increased and the use of this land intensified. In recent years fertiliser usage has decreased (Figure 1) mainly because of reduced farm spending caused by low farm income and increased fixed costs such as interest payments on borrowed money. Associated with the overall increase in fertiliser usage has been an increase in stock numbers up to the current population of 104 million stock units (Figure 1). Pastoral farming therefore operates within an open system where without added nutrients, pasture production levels and stock numbers would fall and the ingress of low-fertility demanding weed and scrub species would proceed.

Changes in soil nutrient status

During pasture development the intitial clearing and burning (and sometimes cultivation) results in a decrease in soil organic matter content (particularly organic C) in the surface soil (Walker *et al.,* 1959).

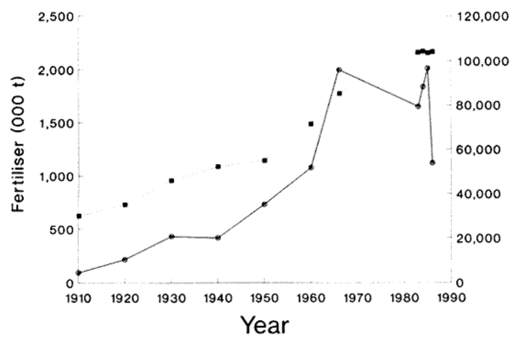

Figure 1: *Amount of fertiliser applied to grassland (--■--) and the number of stock units (——) in New Zealand (New Zealand Agricultural Statistics, 1987).*

Generally in the virgin moderately weathered and leached soils the bulk of the total soil P is present in organic form and there is only a small amount of readily-available inorganic P present in the soil (Saunders, 1959). Thus, although some P may be made available in the ash following burning, generally P deficiency limits clover establishment and growth. Applications of superphosphate (which contains 9% P and 11% S) result in the correction of P deficiency through increasing the soil inorganic P content. There is therefore a large increase in the extractable (çavailableé) inorganic P content of the soil with time under improved pasture (Nguyen *et al.,* 1989). The soil organic P content also increases with time but at a much lower rate (Saunders, 1959; Walker *et al.,* 1959). Thus, Walker *et al.* (1959) observed that whilst organic P made up 90% of total P in soil (0-10 cm) under undeveloped scrub, following 25 years of pasture development the percentage of total P in organic form fell to 55% even though there was an increase in the actual amount of organic P in the soil.

During pasture development there is also an increase in organic S in the soil, the S originating from the superphosphate applications (Walker *et al.,* 1959; Quin and Rickard, 1981).

The addition of P and S in superphosphate enables the clovers to grow vigorously and fix N_2. Nitrogen fixation rates in the order of 100 to 300 kg N ha^{-1} $year^{-1}$ are not uncommon (Hoglund and Brock, 1987). As a result, the N content of the surface soil rapidly increases but the C content generally increases more slowly (Jackman, 1964; Walker *et al.,* 1959). This difference in the rate of accumulation of N and C under pasture is shown in Figure 2. Walker *et al.,* (1959) found that the

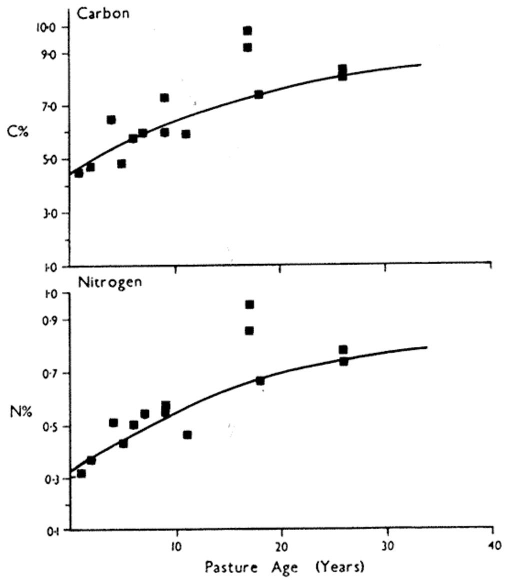

Figure 2: *Effect of pasture age on carbon and nitrogen in the soil (0-7.5 cm; Jackman,* 1964).

C/N ratio of an undeveloped scrub soil was 33 but after 25 years of pasture management the C/N ratio had decreased to 11. The average increase in N content of the top 20 cm of soil was above 100 kg N ha^{-1} $year^{-1}$.

Increases in soil organic matter and a build-up of organic C, N, Sand P under improved pastures have been observed by many workers (e.g., Jackman, 1964; Quin and Rickard, 1981; Perrott and Sarathchandra, 1987). However, organic N, S and P do not necessarily accumulate at the same rate at a particular site and their patterns of accumulation may differ at different sites (Jackman, 1964; Quin and Rickard, 1981). Indeed, accumulation of each element is dependent upon complex interactive cycling processes which are site specific (Stewart, 1984).

Associated with the high soil organic matter content and the dense mass of pasture roots is a large microbial biomass in the pasture rhizosphere. The microbial biomass is therefore usually large under improved pastures and it represents a reasonably large pool of nutrients (e.g., 64 kg N ha^{-1} and 32 kg P ha^{-1}; Sarathchandra *et al.,* 1984; Perrott and Sarathchandra, 1989). The large microbial biomass and high microbial activity under improved pasture contribute to a high level of activity of soil enzymes such as urease, protease, phosphatase and sulphatase (Ross *et al.,* 1984; Sarathchandra *et al.,* 1984, 1988). For example, the data in Table 1 show the sulphatase and phosphatase activities in soil collected from a trial area which has been "improved" with oversowing, grazing and irrigation for 37 years. The trial includes areas with and without annual applications of superphosphate. Soil has also been analysed from an adjacent wilderness site which has been covered in native grasses for at least 37 years and has been neither grazed nor irrigated during this time. Enzyme activities were higher in the irrigated and grazed soil than in the wilderness soil (Table 1). Their activities were further increased by the application of 376 kg superphosphate ha-I every year for 37 years.

Under improved pasture there is a tendency for soil pH to decline over time. Applications of lime every two to four years are often required to maintain soil pH at an optimum level for pasture production (During, 1984). Excretion of H^+ ions in the pasture rhizosphere due to excess cation uptake by the N2-fixing clover (Haynes, 1983) plus nitrification of ammonium in the urine patch and subsequent nitrate leaching (Helyar, 1976) are probably the major contributors to such acidification. An increase in soil cation exchange capacity due to the increasing soil organic matter content (Jackman, 1960) may be another contributing factor.

Nutrient Cycling

In grazed pasture nutrients cycle from the soil to pasture plants and then back to the soil, either through the death of plant tissue or via the excreta of grazing animals as described by Floate (1970a) and illustrated in Figure 3. As the nutrients move through these pathways, losses can occur via removal in animal products, leaching and volatilisation (Figure 3). Gains to the cycle can also occur from rainfall and the addition of fertiliser.

Grazing animals have a major role in the cycling of nutrients and are responsible for increasing the rate at which nutrients are cycled (Floate, 1981). By ingesting herbage, grazing animals encourage pasture plants to grow and therefore take up more nutrients from the soil. In

Table 1: *Effect of long-term grazing and superphosphate applications on organic carbon, sulphatase and phosphatase activity in the surface soil (0-4 em).*

	Wilderness	Irrigated and grazed	
	Area	Nil super	376 kg super
Organic C (%)	3.97	4.18	4.30
Sulphatase activity (µg product/g/h)	67	185	201
Phosphatase activity (µg product/g/h)	1088	1425	1502

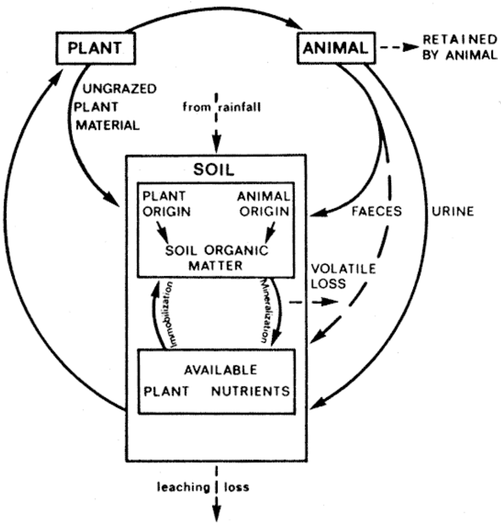

Figure 3: *Generalised cycle of nutrients in grazed pasture (after Floate, 1970a).*

addition, if the herbage is not utilised by the animals but allowed to decompose the N and S cycles will be slower. This is because the N and S in plant tissue are mainly in organic forms which are not immediately available for plant growth, whereas approximately 25% of sulphur excreted and 50% of the nitrogen excreted either are or rapidly become plant available. Floate (l970a, 1981) has shown that release of N (and also P) is much faster via the animal decomposition pathway.

As pastures are improved and their productivity increases, more stock are able to be carried on these pastures and the amount of nutrients moving through the cycle is increased. This can result in large amounts of nutrients being cycled annually. For example, on a farm carrying 20 stock units ha^{-1} it can be calculated that approximately 500 kg N, 300 kg K, 40 kg P and 30 kg S ha^{-1} are recycled each year (data from Cornforth and Sinclair, 1984).

As well as increasing the rate at which nutrients cycle, the grazing animals are also responsible for concentrating nutrients into small volumes of soil affected by dung and urine, distributing nutrients unevenly over the farm and causing significant losses of nutrients from the farm (O'Connor, 1981).

Nutrient return in dung and urine

Grazing animals utilise only a small proportion of the nutrients that they ingest. Approximately 60-99% of the ingested N, K, P, S, Ca and Mg are excreted in the form of dung and urine by sheep and dairy cattle (Hutton *et al.,* 1965, 1967; Joyce and Rattray, 1970a, 1970b; Wilkinson and Lowrey, 1973). Nutrients differ in their pathway of excretion; K is mostly excreted in urine, faeces are the main pathway for the return of P, Mg and Ca, while N and S are excreted in both forms (Barrow, 1987). As a consequence nutrients are spatially separated when they are returned to the soil surface. Thus clover growth can be stimulated by the high amounts of P in the dung where soil P is deficient whereas the N in urine often strongly stimulates grass growth (Sears, 1956).

The surface area of soil covered by dung and urine patches tends to be small. For example, the area covered by a single urination event is 0.22 and 0.03 m^2 for cattle and sheep respectively, and the area covered by a single dung patch is 0.06 and 0.01 m^2 for cattle and sheep respectively (Doak, 1952; Peterson *et al.,* 1956; Davies *et al.,* 1962; Hogg, 1968; Frame, 1971). This means that the total surface area of paddock which receives dung and urine in a year is quite small and may only be 27-40% of the total area (Saunders, 1984). However, due to the high concentration of nutrients in the area affected by excreta (particularly N) pasture growth is encouraged and may be 70% of the total pasture growth (Saunders, 1984).

During a urination event, large quantities of nutrients are applied to relatively small areas of soil. Rates of application can be in the vicinity of 1000 kg K ha^{-1} and 500 kg N ha^{-1} (Saunders, 1984) and these amounts far exceed the immediate needs of the pasture plants growing in the urine patch. Thus complete recycling of nutrients through plant uptake is not achieved. Detailed studies of the processes which can occur in a urine patch have revealed that the following nutrient transformations and movements take place.

1. Urine is a concentrated nitrogen solution (approximately 10 g N $litre^{-1}$) of which 75% is urea (Doak, 1952). In the soil the urea is rapidly hydrolysed to ammonium-N and after several weeks the bulk of this is nutrified to nitrate-N.

2. Due to urea hydrolysis rapid rises in soil pH of up to two pH units occur within 48 hours after a urination event (Doak, 1952; Holland and During, 1977). This rise in pH favours gaseous loss of nitrogen as ammonia. It can also increase the soil's ability to adsorb and retain cations, especially those applied in the urine such as K (Williams *et al.,* 1988).

3. Significant losses of nitrogen can occur through ammonia volatilisation. Such losses have been reported to be in the region of 20-60% of the applied urine-N (Ball and Keeney, 1981; Sherlock and Goh, 1984).

4. The large concentrations of potassium and ammonuim ions which accumulate in the urine patch can result in displacement of native cations (especially Ca and Mg) from soil cation exchange sites and their subsequent loss through leaching (Hogg, 1981; Williams *et al.,* 1990).

5. Large quantities of the mobile nitrate and sulphate anions also accumulate in the soil and leaching losses of these ions can readily occur (Hogg, 1981; Steele, 1987).

6. Urine patches are frequently the site of a physical loss of nutrients. Immediately following a urination event some of the urine flows down through the soil via the macropores created by plant roots, earthworms and soil cracks. If the urine moves in this manner beyond the plant rooting depth then nutrients are lost from the pasture (Williams *et al.,* 1989).

The plant nutrients in urine are either in an immediately available form or are rapidly converted into an available form. However, before the nutrients in dung become available for plant uptake they must be physically incorporated into the soil. Mineralisation may also be necessary for conversion of the organic forms of N, P and S found in dung into inorganic forms before they are available to plants.

Dung can be incorporated into the soil through physical breakdown by soil macrofauna (earthworms and dung bettles), rainfall and the invasion of plant roots into the dung material. It is well established that the rate of breakdown is mainly affected by climate; if the dung remains moist it is rapidly decomposed but if it dries out then decomposition is slow (Weeda, 1967; MacDiarmid and Watkin, 1972; Rowarth *et al.,* 1985). Measurements on the physical breakdown of sheep dung have shown that decomposition is completed within 28 days in winter, but takes at least 75 days in the drier summer conditions (Rowarth *et al.,* 1985).

There is little information on the availability of plant nutrients from dung following incorporation into the soil. Phosphorus in dung is present as both inorganic P, which is immediately plant available, and organic P, which is only slowly mineralised (Barrow, 1987). The ratio of inorganic to organic P depends on the concentration of P and the digestibility of the herbage eaten by the animals, but 75% of the total P may be inorganic (Barrow, 1987). Rowarth *et al.* (1985) found that during dung decomposition the porportions of inorganic and organic P remained constant. This indicates that the major factor affecting P release is the physical breakdown of dung. Nitrogen and S in dung are mainly in organic forms (Watkin and Clements, 1978; Boswell, 1983) and their mineralisation occurs relatively slowly in the soil (Floate, 1970b; Boswell, 1983).

Distribution of dung and urine

Although grazing animals ingest nutrients from all over the paddocks the pattern in which the nutrients are returned via excreta is nonuniform. There tends to be more dung and urine deposited in areas where stock are inclined to camp such as under trees and around water troughs and gateways. For example, fertility transfer was studied by Hilder (1966) using flat paddocks stocked with merino sheep. Because of stock camping, about one third of the total dung was found on less than 5% of the total area of the paddock. The distribution of urine appeared to follow a similar trend.

On hill country pastures the stock tend to camp on flat areas of land and significant quantities of nutrients are transported to these areas from off the steeper slopes where the sheep graze (Gillingham and During, 1973; Gillingham *et al.,* 1980; Rowarth and Gillingham, 1989). Measurements carried out in paddocks with a range of slopes (Rowarth and Gillingham, 1989) have shown that of all the dung returned to the paddock, 60% was deposited on the campsite areas even though they accounted for only 15% of the total area of the paddock (Figure 4). The proportions of dung deposited in the rest of the paddock decreased as slope increased, with only 5% of the dung deposited on slopes greater than 31∫ (Figure 4). This uneven distribution of dung affected the phosphorus status of the soil in the different slopes with the steeper slopes losing phosphorus to the campsite areas (Figure 4). In fact, the phosphorus content in the soil of the campsite areas was increasing by 38% per annum (Figure 4). A similar pattern would be expected for the other nutrients as well.

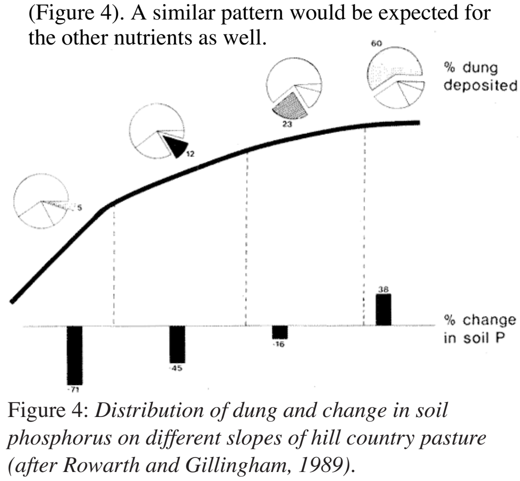

Figure 4: *Distribution of dung and change in soil phosphorus on different slopes of hill country pasture (after Rowarth and Gillingham, 1989).*

In hill country situations, pasture improvement by topdressing is slow (During, 1972) and withdrawal of superphosphate applications can lead to a decline in pasture production (Lambert *et al.,* 1989; O'Connor *et al.,* 1989). The major reason for this is thought to be the significant transfer of P away from the main slopes to the relatively small stock camp areas by the grazing animals (Gillingham *et al.,* 1980; Rowarth and Gillingham, 1989). Net transfer losses of P would directly retard the rate of increase in soil P resulting from superphosphate applications to the main grazing slopes. The consequence would be reduced P availability to pasture legumes and only a slow improvement in N fertility and pasture vigour.

As stocking rate increases there is less tendency for stock to camp and so there is a more even distribution of excreta over the paddock. This leads to reduced transfer losses of nutrients and more efficient cycling of nutrients within the system. Increasing the stocking rate through subdivision of paddocks and the use of rotational grazing rather than set stocking can reduce the camping effects.

Losses of nutrients caused directly by grazing animals

Grazing animals can result in a loss of nutrients from the farm. Losses occur through the removal of animal products in the form of milk, meat, wool, fibre and surplus animals. In addition nutrients are lost in the dung and urine which is deposited in unproductive areas of the farm such as raceways, dairy sheds, yards and feedpads.

The proportion of the ingested nutrients which is exported from the farm in animal products varies widely (e.g., from 1 to 30%; Middleton and Smith, 1978) depending on the nutrient and the type of animal product. On a dairy farm with 20 stock units ha^{-1} losses via milk and surplus animals may be in the order of 82 kg N, 13 kg K, 12 kg P and 4 kg S ha^{-1} (Middleton and Smith, 1978; Field and Ball, 1982; Williams, 1988). In contrast, losses of nutrients in the form of meat and wool from a sheep farm with a stocking rate of 20 stock units ha^{-1} could be 20 kg N, 5 kg K, 3 kg P and 4 kg S ha^{-1} (Wilkinson and Lowrey, 1973; Lambert *et al.,* 1982).

The loss of nutrients due to transfer to unproductive areas of the farm varies between individual farms according to factors such as farm layout and the length of time it takes to handle stock in sheds and yards. For example, on a dairy farm cows spend a significant amount of time in the milking shed each day and the amount of time varies greatly between farms. The use of a feedpad to reduce treading damage to pasture during periods of wet weather or a high soil water table, can also result in significant losses of nutrients. On a dairy farm with an average milking time of two hours per day 6% of the cows' excreta may be deposited off the paddock. For a farm where the milking time takes over three hours per day and the cows spend 25 days a year on a feedpad 17% of the excreta may be deposited off the paddock.

Table 2: *Effect of long-term grazing and superphosphate applications on exchangeable, fixed and total potassium in the surface soil (0-4 cm).*

Soil K Fraction (meq/kg)	Wilderness Area	Irrigated and grazed	
		Nil super	376 kg super
Exchangeable K	6.5	5 . 8	3 . 5
Fixed K	8.3	8 . 4	7 . 7
Total K	446	428	420

Changes in soil nutrient status caused by grazing animals

In a grazed pasture losses of nutrients are inevitable through removal in animal products, transfer off the grazing area in dung and urine, and from urine patches via leaching and volatilisation. With time these losses can cause a reduction in soil levels unless fertiliser is applied to replace these losses. Using the sites described in Table 1 as an example, the effect of 37 years of sheep grazing without the addition of potassium fertiliser has resulted in a decrease in soil .exchangeable and fixed potassium compared with a 'wilderness' soil from an unimproved, non grazed site (Table 2). The data in Table 2 also shows that a high producing pasture which has received 376 kg superphosphate ha^{-1} $year^{-1}$ had a lower exchangeable and fixed soil potassium content compared with an unfertilised improved grazed pasture. This difference occurred because the pasture which received superphosphate was more productive and so carried a higher stocking rate. This resulted in more potassium being cycled and therefore greater losses.

Conclusions

The agricultural productivity of New Zealands grasslands has increased over the last 150 years through the introduction of high producing plant species, the application of fertiliser and intensive grazing management. This has had a beneficial effect on the soil in many situations by increasing the soil nutrient and organic matter content. The grazing animal has both beneficial and negative effects on nutrient cycling. Beneficial effects include greater utilisation of herbage, its rapid decomposition in the animal gut and faster nutrient cycling. The negative impact occurs through the loss of nutrients and concentrating nutrients into small volumes of soil from which complete recovery by plant uptake is difficult. Thus if the nutrient status of the soil under improved pasture is to be maintained at a certain level it becomes necessary to apply fertiliser to compensate for the losses and transfers that are occurring. Fertiliser is an expensive item to both the farmer and the nation, therefore it is necessary to ensure that it is used rationally and economically. The amount of fertiliser required by pastures is based on an understanding of how the nutrients are cycled in a grazed pasture. Since animals excrete most of the nutrients that they ingest it is obvious that a knowledge of the processes which are occurring within the small soil volumes under dung and urine patches will increase our ability to determine and minimise the nutrient requirements of the grazed pasture and so maintain the productivity of our improved pastures.

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