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The calcium requirements of pastures in New Zealand: A review

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Abstract Calcium (Ca) plays a vital role in the structural integrity of soils, plants, and animals. This review considers the Ca status of New Zealand pastoral soils and examines the Ca requirements of pastures and animals. Against this background the diagnostic criteria used to assess Ca requirements for pastures are reviewed. It is concluded that the current Ca concentrations in New Zealand topsoils are more than adequate for optimal pasture and animal production and that this situation is sustainable, based on Ca budgets, given a continuance of the traditional fertiliser practices of superphosphate and liming. For a set of 97 pastoral topsoils, covering all the major soil groups in New Zealand, it was found that soil pH was not related to either exchangeable Ca or Ca saturation (exchangeable Ca/CEC at pH 7). In addition it was found that Ca saturation based on CEC underestimated the Ca saturation calculated from the effective CEC (ECEC). It is likely therefore that soil Ca requirements based on the former would be overestimated. From this and other evidence it is concluded that soil pH should be used as the sole criterion for determining lime requirements.

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INTRODUCTION

Calcium (Ca) plays an essential role in the structure of soils (e.g., aggregate stability, Russell 1973), plants (e.g., structural carbohydrates, Mengel & Kirkby 1982) and animals (e.g., skeleton, Grace 1983). New Zealand soils are, however, relatively young and unweathered and in their virgin state generally contain large amounts of available (i.e., exchangeable) Ca (Metson 1962; Miller 1968). Furthermore, two of the major inputs required to develop legume-based pastures on these young soils were superphosphate and lime (During 1972). Both contain Ca and consequently add significant amounts of Ca to the soil-pasture-animal system. It is perhaps not surprising therefore that there have been no reports of absolute Ca deficiency in animals (Grace 1983) or pastures (Smith & Cornforth 1982) in New Zealand.

In the last decade there have been changes in the fertiliser practices for pastures in New Zealand, with a trend toward high analysis fertilisers and in particular the use of fertilisers which contain no Ca, such as urea and diammonium phosphate (DAP). These practices have implications for the Ca balance of New Zealand pastoral soils. Additionally, there is some confusion in New Zealand with regard to the use and interpretation of some of the diagnostic tests for Ca: does available soil Ca—measured either as exchangeable Ca or Quick Test Ca (QT Ca) (see Cornforth & Sinclair 1984 for definition)—have any diagnostic value independent of soil pH, and does Ca saturation (exchangeable Ca expressed as a percentage of the CEC measured at pH 7) have any diagnostic value?

The purpose of this review is to critically assess the available information on the current Ca status of New Zealand pastoral soils and to assess the current inputs and losses of Ca from the pastoral system, together with those factors likely to affect the soil

Ca balance in the future. Diagnostic criteria for assessing soil Ca are also reviewed.

CALCIUM STATUS OF NEW ZEALAND SOILS

The distribution of exchangeable Ca in 97 New Zealand topsoils, representing all the major soil groups, is given in Table 1. Most of the soils (85%) had exchangeable Ca concentrations > 5 cmol/kg. The one site with exchangeable Ca < 1 cmol/kg was an unimproved Pakahi soil (Hari Hari silt loam) under 4000 mm rainfall and with a soil pH of 5.0 and Ca saturation of 20%. The 14 sites with exchangeable Ca in the range 1–4 cmol/kg were typically coarse textured soils (stony and sandy silts), carrying poor or unimproved pasture and under a rainfall of > 1000 mm. They had soil pHs between 5.0 and 5.9, CECs from 3.5 to 9.2 cmol/kg and Ca saturations between 28–60%.

These recent data are entirely consistent with the soil Ca map published earlier (Metson 1962) based on soil survey information which showed that soils in New Zealand with exchangeable Ca concentrations of < 2 cmol/kg are confined to a few small areas of highly weathered soils such as the podzols, of which the Hari Hari soil mentioned earlier is an example, and unweathered soils derived from parent material with a low Ca content, such as some recent pumice soils, sands, and semi-arid soils.

Consistent with this, Edmeades et al. (1985a) found that the average soil solution concentration of Ca in a range of nine New Zealand topsoils, fertilised for > 50 years and under pasture, averaged 500 μM with a range, due to seasonal fluctuations, of 200–3000 μM. These concentrations are much greater than the critical external Ca concentration required for the maximum growth of temperate grasses and legumes (Bell et al. 1989; Wheeler 1996).

Table 1 Distribution of exchangeable calcium in 97 soils in New Zealand (data from Perrott et al. 1995).

Exchangeable Ca (cmol/kg)	Distribution (%)
<1	1
1–4	14
5–9	49
10–19	27
>20	6

By way of contrast, weathered tropical soils typically have very low levels of exchangeable Ca (Kamprath 1984) and Ca deficiency occurs frequently in a range of crops when the exchangeable Ca concentration is < 1 cmol/kg (<1.5 QT Ca) (Adams & Moore 1983; Kamprath 1984; Bruce et al. 1988; Cregan et al. 1989; McCray & Sumner 1990).

There is a suggestion in the literature that earthworms have a specific and high requirement for Ca and do not thrive on soils with QT Ca < 5 (Stockdill & Cossens 1966). This suggestion originates from survey work conducted by Nielson (1951) who assessed the survival of introduced earthworms at many sites in both the North and South Islands. However, as discussed previously, soils with low exchangeable Ca are frequently coarse textured and can be drought prone. These factors together do not provide a good physical environment for earthworms. Thus, the requirement of earthworms for Ca, as suggested above, may be more apparent than real. Adding Ca to such soil may not guarantee the survival of earthworms because other factors such as the physical environment may be limiting earthworm survival.

CALCIUM REQUIREMENTS FOR PASTURES

McNaught (1969, 1970) published criteria for the concentration of Ca in mixed herbage required for optimal pasture growth, based on samples submitted for advisory purposes. He suggested that Ca concentrations in the range 0.30–1.0% represented "optimal nutrition" and that pasture concentrations greater than this were best described as being "safe excess", on the basis that they did not have a detrimental effect on plant growth or animal production. Using these criteria, Smith & Cornforth

Table 2 Criteria for calcium concentrations in white cover and ryegrass (Cornforth 1984).

	Deficient	Low	Optimum	High
White clover	<0.30	0.30–0.39	0.40–0.50	>0.50
Ryegrass	<0.20	0.20–0.24	0.25–0.30	>0.30

(1982) analysed pasture samples from 5862 sites from throughout New Zealand and found that the mean pasture Ca concentration was 0.73 ± 0.25% (DM) (range 0.10–3.26) and that 86% of the sites fell within the optimal range as defined above, 13% were in the "safe excess" range and only 1% were less than 0.30%.

Cornforth (1984) subsequently adapted the criteria established by McNaught (1969, 1970) by adding an additional category and allowing for the fact that legumes have a higher requirement for Ca than grasses (Metson & Saunders 1978) (Table 2). Other workers (Morton & Roberts 1999; Roberts & Morton 1999) have modified this data further by averaging the above data to provide criteria for mixed pasture samples.

Pasture Ca concentrations in both clovers and grasses exhibit strong seasonal trends as demonstrated in seven sites on the East Coast (Metson & Saunders 1978) and one site in Taranaki (Edmeades et al. 1983b). Pasture Ca concentrations are lowest in the winter and spring and highest in the summer. These changes can be attributed to physiological effects as the plant matures to senescence, together with the seasonal effects on soil solution Ca concentration (Edmeades et al. 1985a).

CALCIUM REQUIREMENTS FOR ANIMALS

Grace (1983) has summarised the relevant New Zealand data on the requirements of ruminant animals for Ca and defined their Ca requirements. His essential data are summarised in Table 3. Comparison of the Ca concentrations required to meet the animal's requirements with the survey data of Smith & Cornforth (1982) indicates that New Zealand's pastures have more than sufficient Ca to meet animal requirements.

Despite this, milk fever (parturient paresis), characterised by low blood plasma Ca (hypocalcaemia), is common in New Zealand in lactating animals, particularly dairy cows. This arises because Ca absorption, and hence blood Ca levels, are not necessarily related to Ca intake (Grace 1983). According to Grace (1983) the absorption of Ca through the small intestine and mobilisation from the bone is controlled by two hormones (parathyroid and calcitonin) and vitamin D. Typically these hormones trigger these processes when the demand for Ca is high, such as during late pregnancy and early lactation. However, in some animals this hormonal response is delayed, exposing the animal to low blood plasma Ca.

Table 3 Animal requirements for calcium (from Grace 1983).

Animal class	Stage of growth	Liveweight (kg)	Weight gain or stage of lactation or milk yield	Calcium requirement (%Ca dry matter)
Sheep	Growing lamb	20	150 g/day	0.29
	Ewe (maintenance)	55	–	0.16
	Ewe (pregnant)	55	late	0.28
Cattle	Growing animal	100	1.0 g/day	0.66
	Dairy cow (maintenance)	380	–	0.22
	Dairy cow (pregnant)	380	9 months	0.36
	Dairy cow (lactation)	380	20 kg/day	0.30
	Beef cow (lactation)	450	10 kg/day	0.35

Table 4 Diagnostic criteria for calcium for optimal production in soil, pasture, and animals.

Component	Measurement	Critical concentration	Typical concentration
Soil	Soil solution	<50 μ*M*	200–3000 μ*M*
	Exchangeable Ca	<1.0 cmol/kg	5–10 cmol/kg
	Quick test[1] Ca	<1.5	8–16
Pasture	Clover	<0.20% DM	0.70% DM
	Ryegrass	<0.30% DM	0.70% DM
Animal	Pasture	<0.40% DM	0.70% DM

[1]See Cornforth & Sinclair (1984) for definition.

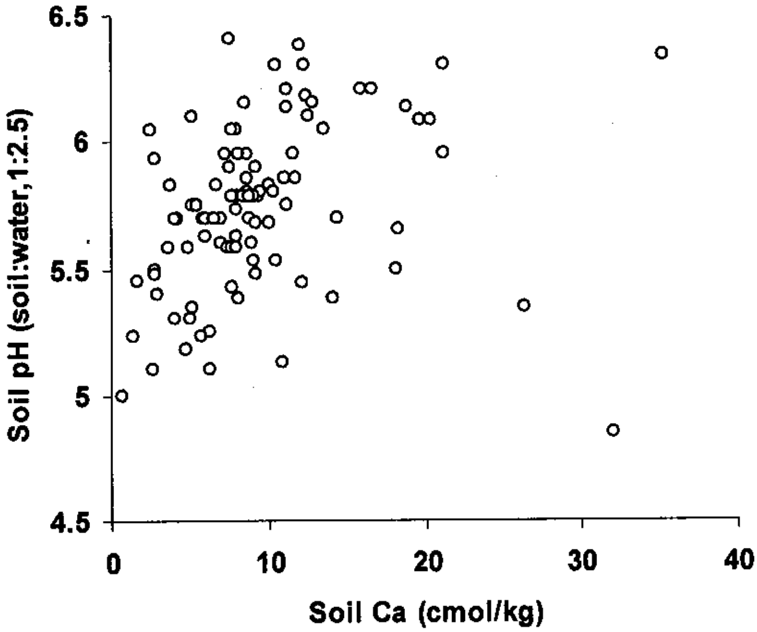

Fig. 1 Relationship between soil pH and exchangeable calcium for 97 topsoils covering a wide range of soil groups and types.

In its acute form, milk fever can only be remedied by intravenous addition of Ca to the animal, normally as Ca borogluconate (Grace 1983). The incidence of milk fever can, however, be reduced by increasing the dietary Mg intake, a cofactor in the production of parathyroid, and paradoxically, by decreasing the dietary Ca intake prior to calving, to stimulate the hormonally-induced release of Ca from the bone (Grace 1983; Roche 2000).

There is some suggestion in the literature that the ratio of Ca:P in the diet has an important effect on the health and growth of animals (Smith & Cornforth 1982). High ratios, it is suggested, decrease the utilisation of P. However, as Grace (1983) points out, this may be so for diets deficient in P, but it does not apply to most New Zealand pastures in which P concentrations are normally adequate (Smith & Cornforth 1982). Thus, providing the P requirements are met, Ca intake has little effect on P utilisation and consequently the ratio of Ca:P is of little diagnostic value to the feeding value of New Zealand pastures.

DIAGNOSTIC CRITERIA FOR CALCIUM

From the results discussed above, the criteria for defining Ca deficiency in pastoral soils, pasture plants, and grazing animals are summarised in Table 4. From this it is clear that the soil Ca status of New Zealand soils is generally more than adequate for optimal pasture and animal production. It is not surprising therefore that "no reports of Ca deficiency [in grazing animals] have been made in New Zealand." (Grace 1983).

Despite the generally high Ca status of New Zealand pastures, applications of ground limestone, which contains Ca, generally increase pasture production if the soil pH is less than 6.0 (Edmeades et al. 1984). Furthermore, the size of the increases in production as a result of liming can be predicted from the initial soil pH (Edmeades et al. 1984). It is reasonable to conclude, therefore, that the cause of such pasture responses to liming is due not to the addition of Ca, but to the change in soil pH resulting from the application of carbonate. This differentiation is important because it is frequently overlooked in the literature. As far as New Zealand soils are concerned, the active ingredient in ground limestone is not the Ca but the carbonate. This is consistent with the observations that dolomite (a Mg carbonate) is as effective as a liming material as limestone (Ca carbonate) (McNaught et al. 1968, 1973).

The resulting change in soil pH can affect the availability of a number of nutrients, depending on the soil and the initial soil pH. At soil pH < 5.5 toxic concentrations of Al and Mn may be present. Increasing the pH decreases their solubility and thus their phytotoxicity (Edmeades et al. 1983a; Smith et

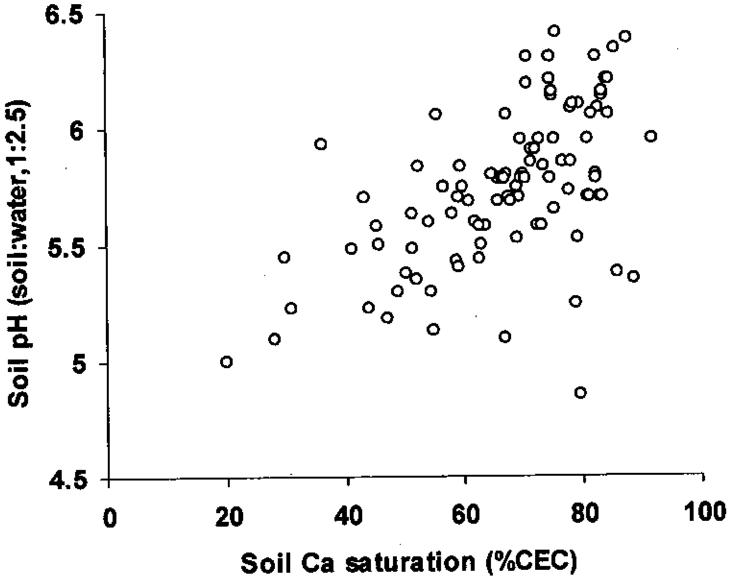

Fig. 2 Relationship between soil pH and calcium saturation (exchangeable Ca/CEC × 100) for 97 topsoils covering a wide range of soil groups and types.

al. 1983). The availability of Mo increases with increasing pH and this can be the reason for pasture responses to liming on Mo-deficient soils (During 1972). Increasing the soil pH up to 5.8–6.0 increases the nett mineralisation of organic N (Edmeades et al. 1981) and this effect can be significant on many New Zealand pastoral soils, which typically have high organic matter concentrations (Edmeades et al. 1986; Wheeler et al. 1997). There is a further category of soils in New Zealand in which the primary benefit of liming occurs through an increase in the availability of P, by decreasing P adsorption and stimulating the mineralisation of organic P (Mansell et al. 1984; Edmeades et al. 1989). As noted elsewhere, determining which mechanism or mechanisms operate in any given situation requires careful experimentation (Edmeades et al. 1995; Edmeades & Ridley 2002).

It is widely assumed that soil pH increases with increasing soil Ca. This assumption is likely to be valid in virgin soils where the primary source of Ca in the parent material is in the form of carbonate. However, in developed soils this may not be valid. The relationship between soil pH and exchangeable Ca for the 97 sites across a wide range of soil groups and types in New Zealand referred to earlier, is shown in Fig. 1. For this set of soils the pH is largely independent of exchangeable Ca. The likely reason for this is that many of these developed soils have had large inputs of Ca as superphosphate. Such products have little or no long-term effect on soil pH and thus the current exchangeable Ca levels reflect past additions of P fertilisers rather than past liming history. Because soil pH is related to pasture production (Edmeades et al. 1984), but is independent of soil exchangeable Ca, the former has been adopted as the sole criteria for liming in New Zealand (During 1972).

In the early literature one of the methods for determining soil lime requirements (i.e., the amount of lime required to achieve a prescribed soil pH) was based on the amount of lime required to achieve a prescribed Ca saturation (i.e., exchangeable Ca/CEC × 100, where CEC is measured at pH 7.0) (Metson 1956; Adams 1984; Lathwell & Reid 1984). Metson used the figure of 60% as the desired value in New Zealand soils. These methods were based on the relationship between soil pH and the Ca saturation. This methodology is still used in New Zealand by some laboratories.

Figure 2 shows the relationship between soil pH and Ca saturation for the set of 97 soils discussed above. It appears that soil pH is also largely independent of Ca saturation. This is consistent with the results reported by Edmeades et al. (1985c), which showed that the soil lime requirement based on Ca saturation was a poor predictor of field-determined lime requirement. Two reasons for this can be suggested. As noted above, current soil Ca levels may reflect past P fertiliser use and not lime use. A further reason is that CEC, as measured at pH 7, overestimates the effective CEC (ECEC)—the

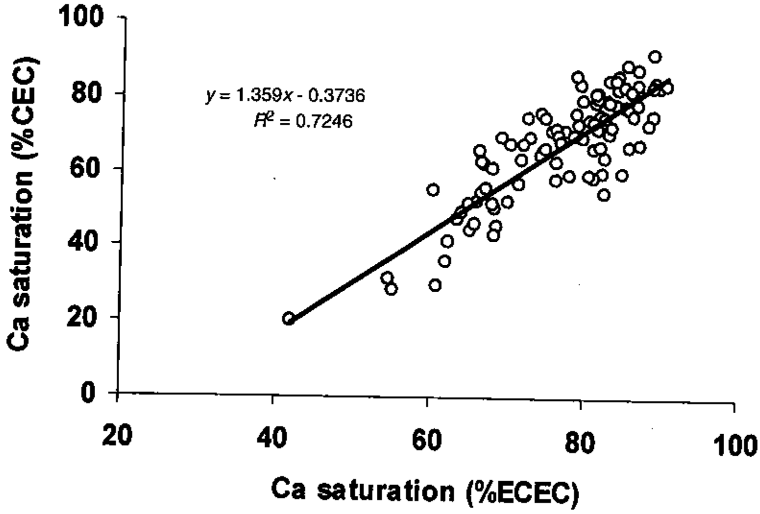

Fig. 3 Relationship between calcium saturation calculated on the basis of cation exchange capacity at either pH 7 (CEC) or at field pH (effective CEC, ECEC) for 97 topsoils in New Zealand.

CEC of the soil at the *in situ* pH. Consequently, the calculated value for Ca saturation is underestimated. This effect can be very large on New Zealand soils (Edmeades 1982) given their relatively high large organic matter content and for some soils their high concentrations of amorphous Fe and Al.

In the case of the subset of 97 New Zealand soils, the relationship between Ca saturation, based on either CEC or ECEC, is shown in Fig. 3. This data suggests that Ca saturation is underestimated by about 10–20% when using CEC. This could mean that requirements for Ca are overestimated if CEC is used as the basis for fertiliser recommendations. This is possibly one reason why fertiliser recommendations based on the base saturation ratio philosophy overestimate some nutrient inputs for no extra gain in productivity (Olson et al. 1982).

In any case, the notion that there are "ideal" saturation ratios for Ca, Mg, and K has now been thoroughly examined and dismissed as a basis for fertiliser recommendations (McLean & Brown 1984; Black 1993). Plant production appears to be unaffected by changes in the ratios of these cations providing the minimum quantity is present to meet plant requirements.

This general conclusion needs to be qualified when animal nutrient requirements are a consideration in the fertiliser advice, as is typically the case for New Zealand pastoral soils. Changing the ratio of Ca:Mg:K:Na in the fertiliser or fertiliser inputs, can affect the concentrations of these nutrients. It is beyond the scope of this review to consider all the possible factors that affect the concentrations of these nutrients in pasture. For a general review readers are referred to Whitehead (2000). In the New Zealand context, Morton et al. (2000) have reviewed the effects of applications of K and N on pasture Ca, Mg, and Na concentrations

Table 5 Calcium budgets for No. 2 Dairy Ruakura with and without fertiliser nitrogen inputs (Ledgard & Roberts 1999).

	Source	Calcium (kg/ha per yr) (average for 2 years)	
		No fertiliser N	400 kg N/ha per yr
Inputs	Rain	5	5
	Fertiliser	130	150
Outputs	Milk	15	20
	Transfer	10	13
	Leaching	100	150
Balance		+5	−28

and Edmeades & O'Connor (2003) have reviewed the effects fertiliser Na and K on pasture cation concentrations. Furthermore, it is known that additions of Ca as limestone can depress pasture Mg concentrations (Edmeades et al. 1983b).

In the context of nutrient ratios, the important point that emerges from this body of research is that the nutritional quality pastures with respect to optimal animal health can be predicted from the concentrations of the respective nutrients in the pasture and soil without the need to invoke the notion of soil and plant nutrient ratios.

CALCIUM BALANCE IN PASTURES

Given that most New Zealand soils currently have adequate reserves of available Ca it is reasonable to ask, is this sustainable?

Ledgard & Roberts (1999) constructed a Ca budget for a high producing dairy farm (3.3 cows/ha producing 1100 kg milk solids (MS)/ha) in the Waikato (Table 5). The largest input of Ca was from fertiliser (applied as superphosphate 600 kg/ha per yr), offset by large leaching losses of between 100–150 kg Ca/ha per year. Significantly, the amount of Ca leached increased with increasing input of fertiliser N, with the consequence that at the high rate of fertiliser N there was a net loss of soil Ca.

There is now a significant body of information on Ca leaching losses from pastoral soils in New Zealand and the various studies are summarised in Table 6. Collectively these data suggest a number of useful generalisations.

It is clear that Ca leaching increases with increasing fertiliser

Table 6 Measurements of leaching losses of calcium.

Study	Year	Treatment	Calcium leached (kg Ca/ha per yr)	Comments	Reference
Manawatu	1932–41	Lime (5 tonne/ha)	130	Indirect measurement[1]	Doak (1941)
Taranaki	1977–79	Lime (7.25 tonne/ha)	650	Indirect measurement[1]	Edmeades et al. (1983b)
Hawkes Bay	1979–94	Lime (7.5 tonnes/ha)	200	Indirect measurement[1]	Wheeler (1997)
Northland	1983	No fertiliser N	154	Direct measurement	Steele et al. (1984)
		170 kg N/ha per yr	216		
Waikato	1995	No fertiliser N	90	Direct measurement	Rajendram et al. (1998)
		200 kg N/ha per yr	90		
		400 kg N/ha per yr	114		
	1996	No fertiliser N	144	Direct measurement	Rajendram et al. (1998)
		200 kg N/ha per yr	162		
		400 kg N/ha per yr	221		
	1997	No fertiliser N	144	Direct measurement	Rajendram et al. (1998)
		200 kg N/ha per yr	162		
		400 kg N/ha per yr	221		
Waikato	1995	No fertiliser N	71	Direct measurement	Rajendram et al. (1998)
Southland	1996	No fertiliser N	69	Direct measurement	Rajendram et al. (1998)
	1997	No fertiliser N	78		
		100 kg N/ha per yr	79		
		200 kg N/ha per yr	92		
		400 kg N/ha per yr	114		

[1]Estimated from the recovery of Ca to a depth of 25 (Manawatu), 20 (Taranaki), and 50 cm (Hawkes Bay).

N inputs. Analysis of the leachates shows that there is a high correlation between Ca and nitrate N, indicating that the Ca cation accompanies the nitrate anion during leaching (Steele et al. 1984; Rajendram et al. 1998). Given that the productivity of legume-based pastures is related to the total N inputs (both as fertiliser N and as symbiotic N fixed by clovers), and that nitrate leaching increases in proportion to N inputs, it is reasonable to suggest that leaching losses of Ca will also increase with increasing pasture productivity.

The amount of rainfall is also an important factor that determines leaching losses of Ca. According to Rajendram et al. (1998), the large year-to-year differences in the amount of Ca leached are directly related to the amount of water passing through the soil. At a broader scale, the losses of Ca when lime is applied were about 8% of the total Ca applied in the two sites on pallic dryland soils in the Hawke's Bay and Manawatu (rainfall < 800 mm) and about 27% on the volcanic soil in Taranaki (rainfall 1500 mm) (Table 6).

In the absence of inputs of fertiliser N and lime, losses of Ca range from 60–150 kg/ha per year (Table 6). This is much higher than the estimate of 10 kg Ca/ha per year quoted by McLaren & Cameron (1990) for forest and extensive farmland, as would be expected given the effect of soil N status on Ca leaching discussed above.

From these generalisations it is possible to construct a Ca budget for a typical dairy farm for comparison with more intensive situations (Table 7). These budgets indicate that providing P is applied as superphosphate and a typical liming programme is followed, then the Ca balance will be positive even under the most intensive management regime. If, however, for the typical farm, superphosphate was replaced by either DAP, triple superphosphate or reactive phosphate rock (RPR), then the net Ca balance would be +24, +56, and +126, respectively. If no lime was used then the balance would be negative (–57).

Given that most farmers have traditionally used both superphosphate and lime, it follows that New Zealand's pastoral soils have been in a net positive balance with respect to Ca. This situation is likely to continue irrespective of the type of P fertiliser used, providing normal liming practices are followed.

A high positive Ca balance is not necessarily desirable. New Zealand soils have a higher affinity for Ca than for Mg, K, and Na (Edmeades & Judd 1980), and hence high inputs of Ca displace the other cations from the exchange sites. This is why excessive Ca additions can increase the leaching losses of Mg, K, and Na (Edmeades et al. 1985b). This increased leaching is likely to be one of the reasons why soil Mg levels in New Zealand pastoral soils are decreasing (Wheeler & Roberts 1997).

It is inevitable that increasing amounts of Mg and Na will be required in the fertiliser mixtures of the future, as soil reserves of these nutrients are depleted. This will be in addition to the Ca and K already applied. When this stage is reached it will be

Table 7 Nutrient budgets for calcium for a typical dairy farm and a high producing dairy farm[1] (Ruakura No. 2 Dairy) with different fertiliser N inputs.

		Amount of calcium (kg Ca/ha per yr)		
	Source	Typical dairy farm	No. 2 Dairy no N	No. 2 Dairy 200 kg N/ha per yr
Inputs	Rain	5	5	5
	Fertiliser	89[2]	130	150
	Lime	170[3]	170	170
	Total	264	305	325
Outputs	Milk	11	15	20
	Transfer	8	10	13
	Leaching	80 + 34[4]	100 + 34[4]	150 + 34[4]
	Total	133	159	217
Balance		+113	+146	+108

[1]Producing 800 kg MS/ha with 2.8 cows/ha.
[2]Fertiliser inputs are 450 kg superphosphate/ha per yr.
[3]2.5 tonnes lime (85% $CaCO_3$)/ha to one-fifth of the farm every year (i.e., 425 kg $CaCO_3$/ha per yr on average).
[4]Assuming an average loss of 80 (in the absence of fertiliser N and lime) plus 20% of the Ca applied in the lime (i.e., 34).

necessary to add these nutrients, Ca, Mg, K, and Na in a ratio suitable to make good the losses of the respective nutrients and to maintain the respective critical soil levels.

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