agKnowledge
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LIME & SOIL ACIDITY

WHY DO WE NEED LIME?

Lime (or more correctly liming materials) has been used in agriculture for centuries and one of the lessons learnt from this experience is contained in folk lore: "Lime and lime without manure makes both farm and farmer poor". The point is true today: lime is not a substitute for fertiliser. Lime is a soil amendment. So why is lime needed?

There are many biochemical reactions which occur is soils which produce acids (symbol H+). For example, one of the most centrally important in our pastoral soils is the breakdown of organic matter, which contains nitrogen (N) by soil micro-organisms to form first, ammonium (symbol NH4+), and then nitrate (symbol NO3-):

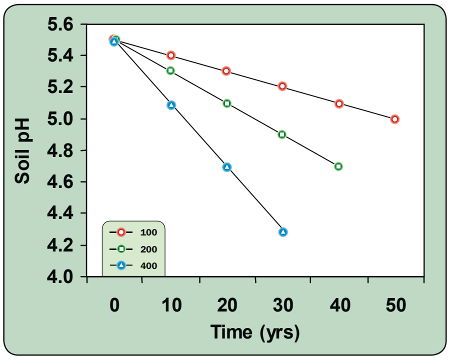
$$\text{soil organic matter} \longrightarrow NH_4^+ \longrightarrow NO_3^- + H^+$$

Many other completely natural biological reactions also create acids, such as the accumulation of soil organic matter – while this is good for the soil in some ways, it also creates an acid soil environment. Surprisingly, fertiliser when applied at the normal rates that are used has very little effect on soil acidity relative to these naturally occurring reactions.

The net effect of all these acidifying reactions is that the soil pH slowly drops – the soil becomes more acid over time. The rate at which this occurs depends largely on the productivity of the farm. For high producing dairy farms the amount of acid is equivalent to 400 to 500 kg lime/ha/yr (This is the amount of lime need to neutralise the acid that is generated) and the pH would decline from 5.5 to 5.0 in a period of 10-15 years if no lime was applied (see figure). In more extensive pastoral systems the rate may only be 100-200 kg/ha lime/yr. In other words starting at pH 5.5 it may take 30-50 years before the soil pH dropped below 5.0.

In any case lime will be required at some stage to maintain the soil pH. **For this reason lime is an essential input required to ensure that the legume-based pastoral industry is sustainable.**

Figure 1. The rate of decline in soil pH over time for 3 rates of soil acidification (100, 200 and 400 kg limestone - equivalents)



SOME SIMPLE CHEMISTRY

The Active Ingredient

When lime (The word lime is used in a generic sense covering all forms of liming materials applied to soil to change the soil pH) is applied to the soil it dissolves and in the process neutralizes (mops-up) the acids in the soil:

$$\underset{\text{[lime]}}{CaCO_3} + \underset{\text{[acid]}}{2H^+} \longrightarrow \underset{\text{[calcium]}}{Ca^{2+}} + \underset{\text{[carbon dioxide]}}{CO_2} + \underset{\text{[water]}}{H_2O}$$

This chemistry says: the more carbonate added the more acid is 'mopped up' and hence the bigger the change in soil pH – the measure of H^+.

The same reaction occurs when pure dolomite (a magnesium (Mg) carbonate) is applied to the soil:

$$\underset{\text{[dolomite]}}{MgCO_3} + \underset{\text{[acid]}}{2H^+} \longrightarrow \underset{\text{[magnesium]}}{Mg^{2+}} + \underset{\text{[carbon dioxide]}}{CO_2} + \underset{\text{[water]}}{H_2O}$$

Thus, a Mg carbonate is just as effective as a Ca carbonate. Alternatively, when say calcium chloride or sulphate is applied to soil Ca is added but the soil pH does not change. In other words **the active ingredient in lime is the carbonate (CO_3^{2-}) not the calcium (Ca)**. This comes as a big surprise to many – **the role of Ca and lime are so often confused.**

New Zealand Soils Have Plenty of Calcium

The table below contrasts the critical levels of Ca in soils, pastures and animals with the typical levels found in New Zealand pastoral systems. This shows that our soils have abundant supplies of Ca. This is a consequence of the Ca-rich parent materials from which they are formed and the fact that they are not very old – they are not greatly weathered. Not surprisingly Ca deficiency in New Zealand soils, pastures and animals is unheard of.

[Note that milk fever arises because at calving the animal cannot mobilise the Ca in its body – it does not arise because our soils and pasture are Ca deficient]

Diagnostic Criteria for Calcium			
Component	**Measurement**	**Critical level**	**Typical levels in NZ**
Soil	exchangeable Ca (me/100 gm)	< 1.0	5 - 10
	Quick test Ca (QT)	< 1.5	8 - 16
Pasture	Clover (% Ca in DM)	< 0.30	0.70
	Ryegrass (% Ca in DM)	< 0.20	0.70
Animal	Pasture (% Ca in DM)	< 0.40	0.70

In addition, New Zealand farmers have historically used lime, superphosphate and RPR, all of which contain significant quantities of Ca. Higher analysis P fertilisers such as triple super and DAP have lower Ca contents or do not contain any Ca.

Calcium content of some products	
Fertiliser	**Calcium Content (%)**
Lime	30 - 40
Superphosphate	20
RPR	30
Triple superphosphate	14
DAP	0

The net effect of these two factors is that **most NZ soils used for agriculture are awash with Ca** –they do not need more Ca. The reason for applying lime to New Zealand soils is not to supply the soil with Ca but to add an alkali (carbonate) to mop-up the acid and hence increase the soil pH.

[It is different in other countries, especially in the tropics, where the soils are so weathered that there is no Ca left in the soil. Liming in these situations is required not only to change the soil pH but also supply Ca]

Most NZ farms have a positive Calcium Balance

Not only are there plenty of reserves of Ca in New Zealand soils but also most farms are in a positive Ca balance – soil Ca will continue to increase.

The inputs and outputs of Ca from a typical dairy farm and a high producing dairy farm are given in Table 2. In both situations the inputs exceed the outputs. The same is true for sheep & beef farms where the demand for Ca is much less. The positive balance is mainly because of the inputs of Ca in lime and super. If DAP was used instead of super as the source of P, both farms would still be in positive balance, but if this was coupled with no lime inputs, both farms would be in deficit (-126 and - 141 kg Ca/ha for the average and high producing farm respectively). Thus, **providing a liming program is in place it does not really matter which P fertiliser is used as a source of P – there will always be a positive Ca balance**.

	Source	**Amounts of calcium (kg Ca/ha/yr)**	
		Average dairy farm[1]	**High producing dairy farm[1]**
Inputs	Rain	5	5
	Superphosphate	89[2]	130[2]
	Lime	170[3]	170[3]
	Subtotal	**264**	**305**
Outputs	Milk	11	15
	Transfer	8	10
	Leaching	114	134
	Subtotal	**133**	**155**
	Balance	**+113**	**+146**

Notes:
1) Average = 800 kg MS/ha. High = 1200 kg MS/ha
2) Average = 450 kg super/ha/yr. High = 600 kg super/ha/yr
3) Lime = 2.5 tonnes/ha/5 yrs.

DETERMINING LIME REQUIREMENTS

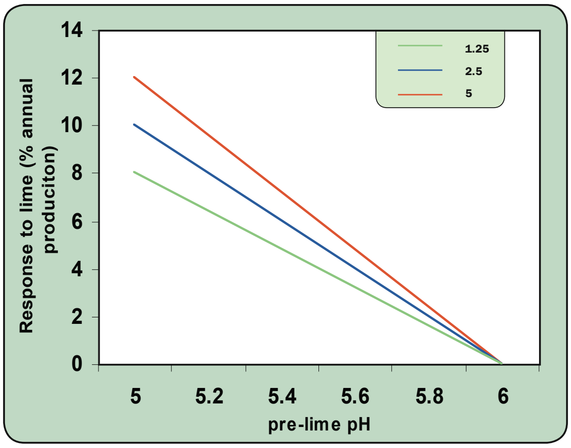
Because the active ingredient in lime is the carbonate (CO_3^{2-}) not the calcium (Ca) it follows that soil Ca is not a useful indicator of the need for lime. **The only criteria for determining if and how much lime is required in a given situation is the soil pH.**

*[**Be very wary of the salesman who recommends lime because the Ca base saturation ratio (BSR) is low**. This can result in applying lime when in fact none is needed and it can have disastrous consequences. The whole concept of BSR is flawed. By this criteria, virtually all New Zealand soils, even those with soil pH levels of 6.0 and above, would need liming, when in fact they have abundant soil Ca levels, as discussed earlier. For further reading see Fertiliser Review No 4 (2000) and 17 (2006)].*

The graph below shows the relationship between the pre-lime soil pH and the size of the annual pasture response to liming at 3 rates (1.25, 2.5 and 5.0 tonnes/ha). For soils with an initial pre-lime pH of 5, liming will increase annual pasture production by about 12% (5 tonnes/ha), 10% (2.5 tonnes/ha) and 8% (1.25 tonnes/ha). Lime responses are greater for the higher rates at low pH levels.

[Qualification: These are the annual pasture responses to liming and it is known that pasture responses are seasonal with the largest responses occurring in the summer and autumn period. Thus an annual response of say 5% may represent a response in the summer or autumn of 15-20% - this would be readily apparent to a farmer].

Figure 2. The effect of soil pH (pre-liming) on the size of pasture response to liming at three rates (1.25, 2.5 and 5.0 tonnes/ha)



As the pre-lime pH increases, the size of the pasture responses to liming decline. For soils with a pH of 5.8-6.0 applying lime has no effect on pasture production. It is therefore the optimal soil pH.

Thus the lime requirement for a given soil is:

(6.0 – pre-lime pH) x the amount of lime required to change the soil pH by 1.0 pH units, which for our soils is 10 tonne/ha (or 1 tonne/ha per 0.1 pH units).

So, on a mineral soil with a pre-lime pH of 5.5 about 5 tonnes ([6.0-5.5] x 10) of good lime are required to achieve a pH of 6.0, the biological optimal pH.

It is different for peat soils. Raw peat contains very little in the way of minerals and the optimal pH is about 5.3-5.5. As the peat decomposes (mineralises) it becomes more like a mineral soil and hence the optimal pH increases with years after cultivation, eventually to 5.8-6.0. Also, because of their high organic matter content the buffer capacity is higher initially.

	Optimal pH	Buffer capacity[1]
Mineral soils	5.8 - 6.0	10 tonne
Raw peat	5.3 - 5.5	12 - 15 tonnes
Developed peat	5.8 - 6.0	3 - 4 tonnes

Notes: 1) the buffer capacity is the amount of lime required to increase the soil pH by 1.0 units

WHAT DOES LIMING DO TO SOILS?

In the international context liming is known to have many effects on soils. But in New Zealand there are no very acid, highly weathered tropical soils, there are no very, very heavy clay soils and no alkaline soils or saline soils. Furthermore, the soil pH levels of the majority of our soils are in the range 5.0 to 6.0 – in fact about 90% are within the range 5.5-6.0.

So, concentrating solely on temperate New Zealand soils used predominantly for growing clover-based pastures the major effects of liming are:

The most important effects of liming on New Zealand pastoral soils are:

1) Increases soil biological activity stimulating the mineralisation of organic matter releasing N. Particularly important over the pH range 5.5 to 6.0.
2) Increases the availability of soil Mo. A positive if on a Mo deficient sedimentary soil. A problem if pasture Mo concentration goes above 1 ppm, which can induce Cu deficiency in animals.
3) Decreases Al and Mn. toxicity. Only important on very acid soils with high concentration of toxic Al and Mn (ie some soils with pH less than 5.5).
4) Decreases the availability of soil Zn and Mn thereby inducing deficiency. Only a problem if the pH is high (> 6.5) on coarse textured soils

It is one, or a combination of these effects, which makes pastures grow better following liming. The size of the pasture response will depend on the initial pre-lime pH (as discussed), the increase in pH following lime application, and of course the composition of the pasture.

*[**Be wary also of salesmen who talks to you about aluminium and manganese toxicity** - these problems will not exist if the soil pH is above 5.5. Similarly, while there is international evidence of liming improving soil structure (and thereby increasing the depth of topsoil or moisture retention), there is no evidence of this on New Zealand soils].*

LIMING MATERIALS

If carbonate is the active ingredient then the different liming materials can be, indeed should be, compared based on how much carbonate they contain which is normally expressed as the lime equivalent assuming 100% pure calcium carbonate. The Table below shows the carbonate equivalents of different liming materials and the cost per unit lime equivalent.

A good quality agricultural lime contains about 80-90% carbonate – in other words it contains 10-20% less carbonate than pure limestone. Expressed differently, 1110 to 1250 kg/ha would have the same effect on the soil pH as 1000 kg/ha of pure lime. Dolomite is more concentrated, having about 98% carbonate. When lime is heated (burnt), calcium oxide is formed from the carbonate. This is more concentrated in terms of its lime equivalents. Only about 560 kg/ha of burnt lime is need to do the same job as a tonne of pure carbonate. Several companies sell, what is called kiln dust, and these contain burnt lime as an impurity.

It is clear from the above that **ground limestone is the cheapest way of applying carbonate to the soil**.

But not all ground limestones are equal as shown below. The Northland limestones typically have lower carbonate content, but when compared on a price per lime-equivalents basis, the cost of ground limestones in NZ ranges between $20-28 per tonne.

Region	Company	Typical Lime equivalent	Particle size		Typical Cost[1] ($/tonne)	Typical Cost ($/tonne lime - equivalent)
			> 2mm %	< 0.5mm %		
Northland	Bellinghams	70	0.2	76.0	17.5	25.0
Auckland	Redvale	70	0.9	67.0	18.0	25.7
Waikato	McDonalds	90	0.3	59.9	18.0	20.0
Hawkes Bay	Hatuma	90	<5.0	>50	18.0	20.0
Nelson	Ngarua	97	0.0	70	23.0	23.7
West Coast	Westport	90	2	60	25.0	27.8
Nth Canterbury	Rangiora	84	3.1	52	22.0	26.2
Sth Canterbury	Geraldine	78	2.5	70	19.5	25.0
Southland	ABLime	93	3.3	64.2	22.95	24.7

Notes: 1) ex-works recommended retail price excluding GST (does not include direct debit discounts etc)

There are some other proprietary liming materials on the market including; dicalcic super, granulated lime (e.g.GranLime) and slurry lime (e.g. pholime, and limephlo). Based on the cost per unit lime equivalents these are very expensive alternatives to ordinary ground limestone.

Product	Lime equivalent (%)	Cost ($/tonne)[1]
Dicalic super (ex Waipawa)	40 - 45	162
Granulated & suspension lime[3]	80 - 110	100 - 200
Slurry lime[3]	80 - 90	> 650

Notes: 1) these costs are 'ex works' and are indicative only
2) typically 95% < 2.00mm and 50% < 0.5 mm
3) typically made from ground micro fine (< 0.01 mm)

Product	Lime equivalent[1]	Amount (kg/ha) to increase pH by 0.1 units[2] ($)	Cost ($)	Transport ($)	Spreading ($)	Total
Limestone	90	1111	20.0	11.1	11.1	42.2
Dolomite	98	1020	102.0	10.2	10.2	122.4
Burnt lime	178	560	101.1	5.6	5.6	112.3
NSD[2]	~100	1000	32	10	10	52

Notes: 1) ex-works recommended retail price excluding GST (does not include direct debit discounts etc)
2) NSD = Nodulated Stack Dust (Westport Cement Plant)

LIME QUALITY AND THE RATE OF DISSOLUTION

Ground limestones are sparingly soluble – they are not insoluble like granite and they do not dissolve immediately like epsom salts. **The rate at which they dissolve in the soil and hence the rate of change in the soil pH depends on 2 important factors: the size of the particles and their hardness.**

The theory says that the finer the material the greater the surface area exposed to the soil and the faster the dissolution. Applying this theory to a typical ground limestone, the table below shows the typical proportions of each size fraction in a tonne of average ground limestone. About 38% is fine (< 250 microns) and all of this material will dissolve within 6 months under normal circumstances. Of the 1000 kg about 190 kg is coarser than 1 mm and this material by comparison dissolves relatively slowly. However by 6 months 75% of the lime (ie 750 kg of the 1000 applied) has dissolved.

Size (mm)	Amount in 1 tonne of lime (kg)	% dissolved in 6 months	Amount of lime dissolved in 6 months (kg)
>1mm	190	31	58.9
>0.5mm	240	59	141.6
>0.25mm	190	91	172.9
<0.25mm	380	100	380
		Total dissolved	**753**

The key point is that a tonne of ground lime contains a range of particle sizes. There are enough 'fines' to ensure a speedy effect (< 6 months) on soil pH and there is coarser material which means that the effects of liming last a long time (3-5 years typically).

But does the theory apply in practice?

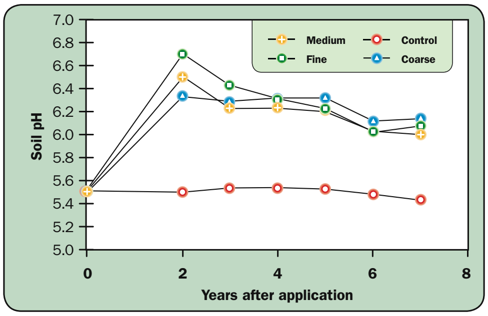
The earliest field trial in New Zealand on the effects of lime on pasture production was conducted in the 1940s. In this experiment three grades of lime were compared at the same rate:

- coarse lime (97% of the particles less than 2.0mm and greater than 0.5mm),
- medium lime (50% of the particles less than 2.0mm and greater than 0.5mm and 50% less than 0.5mm) and
- fine lime (100% less than 0.5 mm).

The changes in soil pH levels over time, following application are shown on the following page:

Compared to the control, all the grades were equally effective. The finer lime "pushed" the pH up more quickly but its effect did not last as long. The coarse material was slower acting but its effect lasted longer. In other words the average soil pH over the trial duration was similar for the 3 treatments (6.1). The theory appears to be true.

The other factor to consider is the hardness of the rock. It turns out that the range in the hardness of New Zealand limestone is not great and experiments show that providing the lime is crushed to the specification given below, there is no difference in the effectiveness of 'hard' and 'soft' limestone.



The Quality Specification

It was on the basis of this type of research that the standards for ground limestone were set. These are:

- not more than 95% of particles larger than 2mm and
- a minimum of 50% of particles smaller than 0.5 mm.

The important point is this: **If the lime you purchase meets this specification then 1) there will be enough 'fines' for a speedy effect and 2) is does not matter whether it is a hard or soft rock.** These rules are applied by Fertmark for registration of ground limestone so if you stick with Fertmark registered products you will not go wrong.

*[Be wary of salesmen who tell you that their lime is very fine and hence less is needed and hence it is cheaper! **The typical story is; because it is so fine, 100 kg/ha is equivalent to 1000 kg/ha of ordinary lime? Such claims defy the laws of chemistry.** They are nonsense. As noted above the effects of lime depend on the size of the pH change and this in turn depends on the amount of carbonate added. Finer equals faster not bigger].*

ANIMAL HEALTH

One of the cherished myths about liming is that it improves animal production and health. This can be true and it can be false – it all depends on the specific conditions.

Liming can improve animal production and health when:

1) It increases pasture growth and hence the animals are better feed. Note pasture responses to liming are seasonal – they are largest in the late summer and autumn.

2) It increases the clover content of the pasture – clover has a higher nutritive value than grasses. This can occur on soils with a pre-lime pH < 5.5 – clover is more sensitive to acidity than grasses.

3) It is applied to Mo deficient soils – liming increases soil Mo availability which greatly enhances clover growth if Mo is deficient.

4) It increases the proportion of the quality grasses (e.g. ryegrass) in the sward. This is likely to happen when liming soils with a pre-lime pH > 5.5 – liming stimulates the breakdown of organic N to which the better grasses respond.

5) It reduces the Mn content of the pasture – high Mn intake can depress the diet especially in lambs. Liming reduces soil Mn availability.

Liming can have negative effects on animal production and health when:

1) It is applied to soils with a pH already above the optimal range 5.8-6.0. Especially on coarse soils, over-liming can cause Mn and Zn deficiency, thus reducing pasture production.

2) It increases pasture Mo levels above 1.0 ppm – this can induce Cu deficiency in animals. Increasing the soil pH can increase soil Mo availability and thus increases pasture Mo concentrations.

3) It is applied at heavy rates (i.e. > 2.5 tonnes/ha) in the early spring. Ingested lime can suppress Mg utilisation in the animal, increasing the incidence of hypomagnesaemia.

THE ECONOMICS OF LIMING

The optimal soil pH for pastures was defined as 5.8-6.0. This is the pH at which pasture growth is maximum –assuming no nutrient limitations. This pH range is called the biological optimal pH to distinguish it from the economic optimal soil pH. The economic pH takes into account whether liming is profitable – what is the bang you get for your lime buck? This of course depends on the costs and prices and hence is specific to a time and a place. Here are some case studies.

[Important qualification: in all the examples below the benefits of liming are based on the average annual pasture response to liming. This approach does not take into account a) the seasonal nature of lime response – a kg DM in the summer/autumn period may be worth much more than a kg in spring and/or b) the effects of liming on pasture palatability and hence pasture utilisation as may occur if liming improves the composition of the pasture. At present there is no known way to factor these effects into the economics].

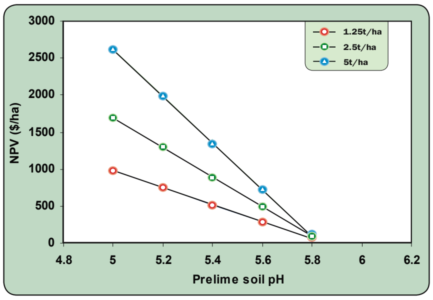
Dairy Farms

Take an average dairy farm and assume the following inputs:

- 950 kg MS/ha.
- Stocking rate of 2.4 cows/ha.
- $5.00/ kg MS payout.
- Variable costs at $400 per cow (This includes: supplements, animal health, cropping, mating and electricity).
- Lime at $23.00/tonne, transport at $12.00/tonne and spreading at $14/tonne (1.25 tonnes/ha) and $9/tonne at 2.5 and 5.0 tonnes/ha.

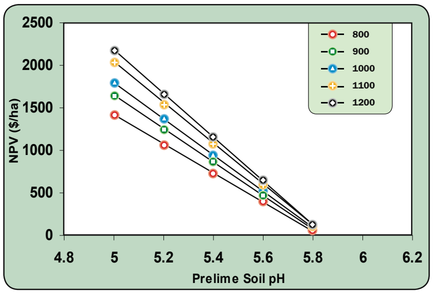
The graph below shows the profit (Net Present Value in $/ha) from liming for different pre-lime soil pH levels.

[The effects of liming last many years - in this example - 5 years. To calculate the profit over the duration of the lime effect we add up all of the annual profits (annual benefits after deducting the cost of the lime) and take into account inflation at 5% per annum. These accumulated annual profits are called the Net Present Value or NPV].



What this shows is that liming is very profitable. On this dairy farm if the current pH was 5.4 the profit accruing from liming (over a 5 year period) is about $1000/ha. That is a handsome return on the investment. For an average sized farm (100 ha) that is $100k extra in the back-pocket! Note also that the economic optimal soil pH is almost the same as the biological optimal pH.

Taking the same inputs as above, the effect of different levels of production (MS/ha) on the profitability of liming (at 2.5 tonnes/ha) can be determined. No surprises here – the higher the production the more profitable liming becomes.



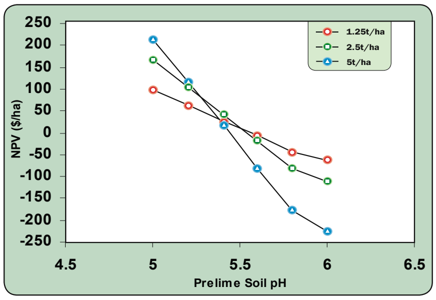
We can play around with other variables. For example, average production in Southland is slightly higher than the Waikato (1000 v 900 MS/ha), but the variable costs are higher because of the additional wintering costs requirements ($400 v $200 per cow) and liming is slightly cheaper in the Waikato ($23 v $18 per tonne). But these differences have little impact on the profitability of liming at 2.5 tonnes/ha. **Liming to soil pH 5.8 to 6.0 is economic (ie the NPV is positive) on all dairy farms,** assuming that the lime is ground spread.

Sheep & Beef Farms

Consider now a 'typical' sheep and beef operation, with the following characteristics:

- Stocking rate at 12 su/ha
- Gross margin of $50/su (the gross margin is the gross income minus the variable costs including, supplements, electricity and animal health).
- Lime at $23.00/tonne, transport at $12.00/tonne and spreading at $15/tonne (1.25 tonnes/ha) and $10/tonne at 2.5 and 5.0 tonnes/ha.

Remember an NPV of > 0 indicates that liming is economic. So in this case, liming at 1.25 or 2.5 tonnes/ha is only profitable if the per-lime pH is 5.5 or below.

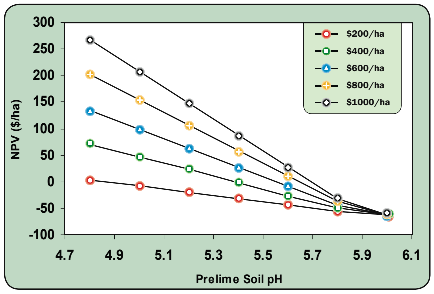


Why the big difference relative the dairy example?

The major driver of the economics of liming is the financial return derived from growing more pasture. This depends on the efficiency of the operation – how many extra dollars income are earned from growing an extra kg of dry matter? And one measure of this is the gross margin per hectare. A typical dairy farm has a gross margin of about $3000/ha. In this sheep and beef example the gross margin is $600/ha (ie the stocking rate x the GM/su = 600). That makes all the difference.

Given that the GM/ha is the major determinant of the economics of liming, it is possible to generalise from the specific case.

The graph below shows the profitability of liming at 1.25 tonnes/ha for 6 levels of GM/ha, using the other input variables as above.



From this information the economic optimal soil pH levels for various types of sheep & beef operations can be deduced as follows:

Gross margin ($/ha)	Economic optimal soil pH	Typical situations
200	< 4.8	Uplands South Island
400	5.0	Dry East Cost < 900 mm SR < 10 su/ha
600	5.4	Central North Island Hill country – 10-12 su/ha
800	5.6	Central North Island Hill country – > 12 su/ha
1000	5.7	Intensive finishing farms

Thus, except for the extensive South Island High Country and the drier regions on the East Coast, **it should be economic to lime the soils to pH level > 5.4**. This is very important because clovers, which are more sensitive to acidity than grasses, need to have a pH of at least 5.2 to grow. Without clover there will be no 'natural' N source going into the soil and without this the legume-based pastoral system will collapse. Which begs the question: are those more extensive farming systems sustainable?