

A summary of the results from fertiliser and lime trials in the eastern region of the North Island

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Abstract

The soils on the eastern region of the North Island (Wairarapa, Tararua, Hawke's Bay, Poverty Bay, East Coast) are mainly of the Brown, Pallic, Recent (Sedimentary) and Pumice orders and are most are farmed with sheep and cattle on hill pastures. Several field trials have been carried out to determine the pasture growth requirements for phosphorus (P), sulphur (S), potassium (K), nitrogen (N), lime and molybdenum (Mo) in this region since the 1960s and the results published in various papers. This review considers the results of these studies collectively and in relation to national datasets. Sedimentary and Pumice soils with Olsen P levels of less than 12 µg/mL required annual application of P. Significant pasture production responses to S were measured where initial soil sulphate-S levels were less than 6 ppm. Additional K for sheep and beef pastures was required mainly on Pumice and Brown soils with soil QTK levels of 6 or less. Large pasture DM responses to N were measured in most trials, especially on steep slopes and sunny aspects with low legume content. Lime is needed to maintain soil pH once it decreases to 5.4 on hill soils. Molybdenum deficiency in legumes can occur on sedimentary soils and should be monitored by clover-leaf analysis.

Keywords: lime, nitrogen, pasture production, phosphorus, potassium, sulphur

Introduction

The eastern region of the North Island is bounded by the Tararua, Ruahine, Kaweka, Maungaharuru, Huiarau and Raukumara Ranges to the west. Most of the approximately 1.5 million hectares of pastoral land is farmed with dryland sheep and cattle (annual rainfall 600–2000 mm) with a smaller area of dairy farming concentrated under higher annual rainfall (>2000 mm) mainly in the shadow of the Tararua and Ruahine Ranges or under irrigation on the Ruataniwha Plains in Central Hawke's Bay. Of the total area in pasture, about 40% is on steeper hill country, about 40% on easier sloped land and about 20% on flatter land able to be cropped (S. Lys, Beef + Lamb NZ, pers. comm.). Most of the sheep and beef farms are on Brown soils on the hills, Pallic soils formed on terraces and hills and

Pumice soils on rolling land and easy hills in Northern Hawke's Bay and Poverty Bay/East Coast (Dowling 1999; Falloon 2015). Dairying is carried out mainly on Recent and Allophanic Brown soils. Drainage is most free on Pumice soils with Brown and Recent soils moderately drained and Pallic soils the poorest drained (McLaren & Cameron 1984). Water-holding capacity ranges from low on Pumice and Pallic soils to moderate on Brown and Recent soils (McLaren & Cameron 1984). Anion storage capacity increases from Recent (10–20%) to Pallic (20–30%) to Brown (30–50%) to Pumice (50–70%) soils (McLaren & Cameron 1984). All the soils have moderate ability to retain cations but Recent and Pallic soils can supply more potassium (K) (McLaren & Cameron 1984). Soil calcium levels are generally adequate for pasture growth following lime and superphosphate applications (Morton et al. 2019) while soil magnesium levels are only low for pasture growth on a few Pumice soils (McLaren & Cameron 1984). There is no scientific evidence for the requirement of trace elements such as boron, copper, manganese and iron for grass/legume pastures on these soils in this region. Eastern region sheep and beef farms have received mainly superphosphate-based fertiliser products and have been limed when finances permitted.

A number of trials have been carried on the fertiliser and lime requirements of sheep and beef pastures, (the pre-dominant farming systems in this region) since the 1960s. Pasture dry matter (DM) and animal growth-response results of these trials have been published in various papers (see Tables for details) but have not been presented collectively. Many of the datasets have already been included in National Databases of pasture production trials carried out in New Zealand (Edmeades et al. 1984, 2005, 2006, 2010) but have not been examined for regional trends. Also, a summary of regional data will be valuable for consultants and farmers and provides a single, easily accessible source of information for end-users.

Trial Results

Phosphorus

Phosphorus (P) is required on all soils in the region to replace soil and grazing losses but adding P is costly as it is the most expensive major nutrient in fertiliser. Results from P response trials are summarised in Table 1.

Table 1 The effect of P on pasture production and animal growth.

Location	Soil order	Topography	Average rainfall (mm/yr)	Trial technique	Duration of reported results (yrs)	Previous fertiliser history	Initial soil Olsen P ($\mu\text{g/mL}$)	Rates of P (kg/ha/yr)	Initial dominant pasture species	Response in pasture production	Response in animal production	Reference
Te Araroa	Brown	Hill	1980	Small plot mowing – one spring and one autumn cut	2	125 kg superphosphate/ha/yr	12	0,20,40,80	Browntop/ryegrass/white clover	18% increase in Yr 2 (P<0.05)		O'Connor & Gray (1984)
Te Araroa	Brown/Pumice	Hill	1980	Small plot mowing – one spring and one autumn cut	2	125 kg superphosphate/ha/yr	11	0,20,40,80	Browntop/ryegrass/white clover	Non-significant (P>0.05)		O'Connor & Gray (1984)
Tolaga Bay coastal	Brown/Pumice	Hill	1500	Small plot mowing – one spring and one autumn cut	2	Nil	6	0,20,40,80	Browntop	65 and 40% increase in Yrs 1 and 2 (P<0.001)		O'Connor & Gray (1984)
Tokomaru Bay coastal	Brown	Hill	1790	Small plot mowing – one spring and one autumn cut	2	250 kg superphosphate/ha/yr	13	0,20,40,80	Browntop/ryegrass/white clover	Non-significant (P>0.05)		O'Connor & Gray (1984)
Ruatoria	Allophanic*	Hill	1800	Small plot mowing – one spring and one autumn cut	2	Nil	4	0,20,40,80	Browntop	70 and 84% increase in Yrs 1 and 2 (P<0.001)		O'Connor & Gray (1984)
Tolaga Bay inland	Pumice/Allophanic*	Hill	1670	Small plot mowing – one spring and one autumn cut	2	250 kg superphosphate/ha/yr	9	0,20,40,80	Browntop/ryegrass/white clover	24% increase in Yr 2 (P<0.001)		O'Connor & Gray (1984)
Tokomaru Bay inland	Pumice/Allophanic*	Hill	1540	Small plot mowing – one spring and one autumn cut	2	250 kg superphosphate/ha/yr	22	0,20,40,80	Ryegrass/browntop/white clover	Non-significant (P>0.05)		O'Connor & Gray (1984)
Matawai	Pumice*	Hill	1770	Small plot mowing – one spring and one autumn cut	2	375 kg superphosphate/ha/yr	7	0,20,40,80	Ryegrass/browntop/white clover	24 and 26% increase in Yrs 1 and 2 (P<0.001)		O'Connor & Gray (1984)
Waipawa	Pallic	Hill	800	Sheep and cattle grazing in small paddocks with exclusion cages	4		9 (Low P) 28 (High P)		Browntop/subterranean and white clover	25% increase from High vs Low P (P<0.01)	8% increase in animal liveweight	Gillingham et al. (2003) Gillingham et al. (2004)
Waipawa	Pallic	Hill	800	Sheep and cattle grazing in small paddocks with exclusion cages	3		15 (Mod P) 28 (High P)		Browntop/subterranean and white clover	14% increase from High vs Mod P (P<0.01)	17% increase in animal liveweight	Gillingham et al. (2003) Gillingham et al. (2004)
Wairoa	Pumice	South aspect 0-15° slope	1348	Small plot mowing with clippings removed	3		11	Varied between years but ranged from 0 to 160 kg P/ha/yr	Browntop/ryegrass/white clover	Significant in all years (P<0.05)		Gillingham et al. (2007)
Wairoa	Pumice/Brown	South aspect about 20° slope	1348	Small plot mowing with clippings removed	3		5	Varied between years but ranged from 0 to 160 kg P/ha/yr	Browntop/white clover	Significant in all years (P<0.001)		Gillingham et al. (2006)
Puketapu	Pallic	South aspect 0-15° slope	826	Small plot mowing with clippings removed	3		6	Varied between years but ranged from 0 to 160 kg P/ha/yr	Browntop/ryegrass/white clover	Significant in all years (P<0.05)		Gillingham et al. (2007)
Puketapu	Pallic	North aspect about 20° slope	826	Small plot mowing with clippings removed	3		4	Varied between years but ranged from 0 to 160 kg P/ha/yr	Browntop/white clover	Significant in all years (P<0.05)		Gillingham et al. (2008)

Waipawa	Pallid	North aspect 0-15° slope	869	Small plot mowing with clippings removed	3	4	Varied between years but ranged from 0 to 160 kg P/ha/yr	Browntop/ryegrass/subterranean and white clover	Significant in Yrs 2 and 3 (P<0.001)	Gillingham et al. (2007)
Waipawa	Pallid	North aspect about 20° slope	869	Small plot mowing with clippings removed	3	6	Varied between years but ranged from 0 to 160 kg P/ha/yr	Browntop/subterranean clover	Non-significant (P>0.05)	Gillingham et al. (2008)
Wallingford	Pallid	South aspect 0-15° slope	893	Small plot mowing with clippings removed	3	8	Varied between years but ranged from 0 to 160 kg P/ha/yr	Browntop/white clover	Significant in Yrs 2 and 3 (P<0.05)	Gillingham et al. (2007)
Wallingford	Pallid	West aspect about 20° slope	893	Small plot mowing with clippings removed	3	6	Varied between years but ranged from 0 to 160 kg P/ha/yr	Browntop/white and subterranean clover	Significant in all years (P<0.01)	Gillingham et al. (2008)
Gladstone	Brown	Flat	846	Small plot with clippings removed	3	12	Varied between years but ranged from 0 to 160 kg P/ha/yr	Browntop/ryegrass/white clover	Significant in Yr 3 (P<0.01)	Gillingham et al. (2007)
Gladstone	Brown	North aspect about 20° slope	846	Small plot mowing with clippings removed	3	9	Varied between years but ranged from 0 to 160 kg P/ha/yr	Browntop/subterranean clover	Significant in all years (P<0.01)	Gillingham et al. (2008)

* Soils reclassified by Gray et al. (1988)

The pasture-production responses to P from the East Coast/Poverty Bay series of trials (O'Connor & Gray 1984) were largest where initial soil Olsen P levels were low (generally less than 12 µg/mL) and fertiliser had not been applied previously. The smallest pasture-production responses occurred on soils with higher soil Olsen P levels and where adequate fertiliser had been applied regularly. The high initial Olsen P values obtained for some Pumice soils could be attributed to their lower bulk density in a laboratory analysis based on a volume of soil. In both the Waipawa grazing trials (Gillingham et al. 2003, 2004) and the series of small plot trials (Gillingham et al. 2007, 2008), nitrogen (N) was applied with the P but no significant (P>0.05) interactions in pasture production were measured between P and N. Mackay et al. (2010) reported a similar relationship between soil Olsen P and relative pasture production at 0 and 400 kg N/ha/yr. Pasture production responses to P tended to be more significant on easy slopes that had more legume compared to sites with steeper slopes and occurred at all of the lower (generally less than 12 µg/mL) soil Olsen P levels (Gillingham et al. 2007, 2008). In this series of small plot trials, there were curvilinear relationships between soil Olsen P levels and relative pasture production at the Wairoa, Waipawa and Wallingford easy sites and Wairoa steep site that were similar to the relationships derived by O'Connor & Gray (1984) and Edmeades et al. (2006).

Sulphur

Like P, sulphur (S) is also naturally low in most New Zealand soils and requires annual application in intensive farming systems. The pasture production responses to S from trials in the eastern region of the North Island are shown in Table 2.

A range of 10-12 ppm S is required for near-maximum pasture production (Morton & Roberts 2016) and sulphate-S levels in the East Coast soils were mostly below the 10-ppm threshold. However, a large, consistent response in pasture production to the addition of S was measured only at one site, which had a very low natural level of 1 ppm (O'Connor & Gray 1984; Table 2). The lack of response at the other sites studied may have been due to the predominance of low fertility-demanding browntop and little S-responsive clover in the swards. Results from the other trial series (Nguyen et al. 1989) showed increased pasture production in response to S at three of the five sites studied despite lower or equal annual rainfall and higher soil sulphate-S levels than in the other trial series. For the two of the three S-responsive sites, it appeared that insufficient of the sulphate-S applied in the previous summer/autumn was retained until the next spring while the other responsive site had no S

Table 2 Pasture production responses to S from small plot mowing trials.

Location	Soil order	Topography	Annual rainfall (mm/yr)	Duration (yrs)	Previous fertiliser history	Initial soil sulphate-S level (ppm)	Rates of S (kg/ha/yr)	Pasture production response	Reference
Te Araroa	Brown	Hill	1980	2*	125 kg superphosphate/ha/yr	4	0, 44 (mixture of gypsum and elemental S)	Non-significant (P>0.05)	O'Connor & Gray (1984)
Te Araroa	Brown/Pumice	Hill	1980	2*	125 kg superphosphate/ha/yr	9	0, 44 (mixture of gypsum and elemental S)	Non-significant (P>0.05)	O'Connor & Gray (1984)
Tolaga Bay coastal	Brown/Pumice	Hill	1500	2*	Nil	6	0, 44 (mixture of gypsum and elemental S)	Non-significant (P>0.05)	O'Connor & Gray (1984)
Tokomaru Bay coastal	Brown	Hill	1790	2*	250 kg superphosphate/ha/yr	1	0, 44 (mixture of gypsum and elemental S)	13% (P<0.05) and 19% (P<0.001) increase in Yrs 1 and 2	O'Connor & Gray (1984)
Ruatoria	Allophanic	Hill	1880	4*	Nil	9	0, 44 (mixture of gypsum and elemental S)	Non-significant (P>0.05)	Gray et al. (1988)
Tolaga Bay inland	Pumice/Allophanic	Hill	1670	4*	250 kg superphosphate/ha/yr	8	0, 44 (mixture of gypsum and elemental S)	Non-significant (P>0.05)	Gray et al. (1988)
Tokomaru Bay inland	Pumice/Allophanic	Hill	1540	4*	250 kg superphosphate/ha/yr	8	0, 44 (mixture of gypsum and elemental S)	Non-significant (P>0.05)	Gray et al. (1988)
Matawai	Pumice	Hill	1770	4*	375 kg superphosphate/ha/yr	6	0, 44 (mixture of gypsum and elemental S)	Non-significant (P>0.05)	Gray et al. (1988)
Hawke's Bay	Pallic		900	0.25	250 kg superphosphate/ha/yr in autumn	12	0, 50 (mixture of gypsum and fine elemental S)	Significant (P<0.05)	Nguyen et al. (1989)
Hawke's Bay	Brown		1200	0.25	125 kg/ha S superphosphate in the previous autumn	15	0, 50 (mixture of gypsum and fine elemental S)	Non-significant (P>0.05)	Nguyen et al. (1989)
Hawke's Bay	Pumice		1600	0.25	Regular summer/autumn application of up to 300 kg/ha superphosphate	12	0, 50 (mixture of gypsum and fine elemental S)	Significant (P<0.01)	Nguyen et al. (1989)
Hawke's Bay	Pumice		1600	0.25	325 kg/ha S superphosphate in previous autumn	30	0, 50 (mixture of gypsum and fine elemental S)	Non-significant (P>0.05)	Nguyen et al. (1989)
Hawke's Bay	Pumice		1600	0.25	No S for 4 years before trial	9	0, 50 (mixture of gypsum and fine elemental S)	Significant (P<0.01)	Nguyen et al. (1989)

* One cut in spring and one in autumn

applied for four years. Also, two of the three responsive sites were on Pumice soils that have medium to high anion storage capacities (ASC) but well to excessive soil drainage. These attributes mean that the soils do not retain a large amount of sulphate-S during winter (Edmeades et al. 2005).

Sulphur and potassium

An interaction between application of S and K was observed at the three sites with Brown or Pumice/Allophanic soils that had soil QTK levels of 2, 4 and 4 (Table 4) (Gray et al. 1988). In these cases, the pasture production response to S was much greater and significant ($P < 0.05$) when K was applied.

Phosphorus and sulphur

Phosphorus and S are usually applied together as superphosphate on most farms in the eastern region of the North Island. A smaller number of farms receive P and S as Reactive Phosphate Rock (RPR)/elemental S mixes. Three trials that measured pasture and animal production responses to superphosphate and/or RPR/S have been carried out in the eastern region of the North Island (Table 3).

The results from the farmlet grazing and two small

plot mowing trials are consistent with pasture production responses from other trial sites with a similar soil Olsen P level (Edmeades et al. 2006). These results also show the lack of suitability for RPR as a P fertiliser under lower annual rainfall as shown from the National Series of Forms of Phosphorus (Sinclair 1989).

Potassium

Potassium (K) is required on most dairy farms and can be required on sheep and beef farms on Pumice and Brown soils under high annual rainfall (> 1500 mm). High rainfall increases winter leaching of urine K and there tends to be more clover growth (which is K-demanding) under the less selective grazing by cattle where there is a high ratio of cattle to sheep ($> 50:50$) (Boswell 1976). Also, sheep recycle urine K more efficiently than cattle (Morton unpublished data). There have been two series of K response trials carried out in the eastern region of the North Island (Table 4).

In the first East Coast/Poverty Bay series of mowing trials, O'Connor and Gray (1984) (Table 4), the general lack of pasture production response to K on Brown soils and Brown/Pumice soils would be expected because most of the QTK levels were above the critical level of 6 for 97% of maximum pasture production for Brown

Table 3 Pasture production responses from P and S fertilisers.

Location	Soil order	Topography	Annual rainfall (mm/yr)	Duration (yrs)	Dominant pasture species	Trial technique	Initial soil Olsen P level ($\mu\text{g/mL}$)	Initial soil sulphate-S level (ppm)	Rates of P (kg/ha/yr)	Rates of S (kg/ha/yr)	Pasture production response	Reference
Woodville	Brown	Easterly to northerly aspect – easy to steep hill	1276	13	Browntop/sweet vernal/dogtail	Small paddocks with exclusion cages	6		11, 33	14, 42	Average 37% increase ($P < 0.01$) for 375 kg superphosphate/ha/yr over 125 kg superphosphate/ha/yr	Lambert et al. (2014)
Waipukurau	Pallic	Flat	650	6	Ryegrass/browntop/white clover	Small plot mowing	8	9	0, 11 – 15	0, 3 – 18	Significant response ($P < 0.05$) to S superphosphate over control Non-significant response ($P > 0.05$) to North Carolina/elemental S over S superphosphate or control	Craighead (2004)
Masterton	Pallic	Easy hill	950	6	Ryegrass/browntop/white clover	Small plot mowing	7	4	0, 13 – 27	0, 10 – 28	Significant response ($P < 0.05$) to S superphosphate over control Non-significant response ($P > 0.05$) to North Carolina/elemental S over S superphosphate or control	Craighead (2004)

Table 4 Pasture production responses to K from small plot mowing trials.

Location	Soil order	Topography	Annual rainfall (mm/yr)	Duration (yrs)	Initial dominant pasture species	Initial soil QTK level	Rates of K (kg/ha/yr)	Pasture production response to K	Reference
Te Araroa	Brown	Hill	1980	2	Browntop/ryegrass/white clover	6	0, 160*	37% increase in Yr 1 (P<0.01)	O'Connor & Gray (1984)
Te Araroa	Brown/Pumice	Hill	1980	2	Browntop/ryegrass/white clover	12	0, 160*	Non-significant (P>0.05)	O'Connor & Gray (1984)
Tolaga Bay (Coastal)	Brown/Pumice	Hill	1500	2	Browntop	10	0, 160*	Non-significant (P>0.05)	O'Connor & Gray (1984)
Tokomaru Bay (Coastal)	Brown	Hill	1790	2	Browntop/ryegrass/white clover	12	0, 160*	Non-significant (P>0.05)	O'Connor & Gray (1984)
Ruatoria	Allophanic	Hill	1880	4	Browntop	7	0, 120*	Non-significant (P>0.05)	Gray et al. (1988)
Tolaga Bay (Inland)	Pumice/Allophanic	Hill	1670	4	Browntop/ryegrass/white clover	4	0, 120*	Overall significant (P<0.05)	Gray et al. (1988)
Tokomaru Bay (Inland)	Pumice/Allophanic	Hill	1540	4	Ryegrass/browntop/white clover	4	0, 120*	Overall significant (P<0.05)	Gray et al. (1988)
Matawai	Pumice	Hill	1770	4	Ryegrass/browntop/white clover	2	0, 120*	Overall significant (P<0.05)	Gray et al. (1988)
Waipawa	Pallic	North aspect - 0 - 15° slope	869	3	Browntop/ryegrass/white and subterranean clover	4	Rates varied from 0 to 160**	Non-significant (P>0.05)	Morton et al. (2017)
Waipawa	Pallic	North aspect - about 20° slope	869	3	Browntop/subterranean clover	5	Rates varied from 0 to 160**	Non-significant (P>0.05)	Morton et al. (2017)
Puketapu	Pallic	South aspect - 0 - 15° slope	826	3	Browntop/ryegrass/white clover	3	Rates varied from 0 to 160**	Significant in Yr 3 (P<0.05)	Morton et al. (2017)
Wairoa	Pumice	South aspect - 0 - 15° slope	1348	3	Browntop/ryegrass/white clover	3	Rates varied from 0 to 160**	Non-significant (P>0.05)	Morton et al. (2017)
Wairoa	Pumice	South aspect - about 20° slope	1348	3	Browntop/white clover	2	Rates varied from 0 to 160**	Non-significant (P>0.05)	Morton et al. (2017)

* clippings discarded; ** 50% of clippings returned

soils and 7 for Pumice soils (Edmeades et al. 2010). The responsive site on these soils was at Te Araroa (QTK level of 6). One out of the four sites studied by Gray et al. (1988) did not respond to K. The non-responsive site (at Ruatoria) had Allophanic soil and had a QTK level of 7, i.e. greater than the critical level of 5 described by Edmeades et al. (2010) for this soil order. In contrast, the responsive sites (Matawai, Tokomaru Bay inland and Tolaga Bay inland) had Pumice/Allophanic soils with QTK levels of 2 and 4 (Table 4), i.e. below the critical levels of 6 and 5 for these soil orders respectively.

There was a lack of overall response in pasture production to K at lower soil QTK levels in the trial series published by Morton et al. (2017) despite the measurement of clover DM responses. This general lack of response was attributed to the presence of more grass compensating for less clover growth at the lower rates of K and/or the inefficient transfer of nitrogen (N) from clovers to grasses that limited grass growth. In this trial series, the return of about half the mown clippings simulated urine return under sheep grazing. The trial results indicated total DM production response to K increased over time so significant responses may have been measured if the trials had been continued for longer than three years.

Nitrogen

Since the 1980s, increasing amounts of N fertiliser have been applied to New Zealand pastures, especially on dairy farms. There have been several N-response trials on sheep and beef pastures carried out in this region (Table 5).

High efficiencies of response were recorded on hill country sites with low soil N content across all trial series. Spring application of N was more efficient than autumn application, and responses in pasture production increased with greater slope and on sunny aspects that had less legume. Also, the efficiency of response to N generally decreased as N rate increased.

Lime

Most pastoral soils have low natural soil pH and require lime to neutralise the effects of acidification. Lime trial results in this region are summarised in Table 6.

Liming significantly increased pasture production when soil pH was less than or equal to 5.5, which is consistent with results from other lime trials reported by Edmeades et al. (1984). There was a greater response in pasture production to lime from shady vs sunny aspect and easy vs steep slope (Morton et al. 2005). One reason for this effect could be the addition of lime alleviating toxicity of soil aluminium (Al) in the areas with a greater content of white clover, a species that is sensitive to Al (Morton et al. 2005).

Molybdenum

O'Connor & Gray (1984) measured significant ($P < 0.05$) pasture production responses to molybdenum (Mo) at three hill country sites on Brown soils with soil pH of 5.3 and 5.4. Morton & Morrison (1998) reported a significant ($P < 0.05$) response in clover and total DM production on a Pallic soil (pH 5.6) near Carterton with a low clover Mo content of 0.06 ppm and a low clover N content of 3.6%.

General Discussion and Recommendations

Although these trial results only made up a small proportion of the datasets in the National Databases, they generally supported the overall results as summarised by Morton & Roberts (2016) and Morton et al. (2019). The following general recommendations for nutrient and lime use for sheep and beef farms in the eastern region of the North Island can be made:

1. Most of the reported trial sites had soil Olsen P levels of less than 12 $\mu\text{g/mL}$. In general, there was a significant response in pasture production to applied P, which was consistent with the overall relationship between soil Olsen P and relative pasture growth for both Sedimentary and Pumice soils from the National Database (Edmeades et al. 2006). The target soil levels for Olsen P that will sustain near-maximum pasture production are 20–30 $\mu\text{g/mL}$ for Sedimentary soils and 35–45 $\mu\text{g/mL}$ for Pumice soils (Morton & Roberts 2016) but the economic soil Olsen P levels will be more likely to be 15–20 $\mu\text{g/mL}$ on Sedimentary (Morton & Roberts 2016) and 20–25 $\mu\text{g/mL}$ on Pumice soils for a typical hill country sheep and beef farm carrying 10 SU/ha. The regional trials were not of sufficient duration to establish maintenance fertiliser P rates and these are best determined by measuring trends in soil Olsen P levels over time for each individual farm (Morton & Roberts 2016). Maintenance fertiliser P rates range from 6–28 kg/ha/yr for stocking rates of 7–13 SU/ha (Morton & Roberts 2016).
2. Most of the trial sites had initial sulphate-S levels of greater than 6 ppm and there was no measured response in pasture production although pasture production responses to S were measured for some soils with initial levels of greater than 6 ppm. In these cases, either S in the more leachable sulphate-S form had been applied later in the growth season or no S had been applied in the preceding period. The relationship between soil sulphate-S and relative pasture growth for all soil groups in the National Database (Edmeades et al. 2005) shows a levelling-out of pasture growth above a soil sulphate-S level of 6 ppm. At the three sites where significant responses in pasture production to S were measured, 40–50 kg S/ha/yr were applied which is above or within

Table 5 Pasture production responses to N.

Location	Soil order	Topography	Annual rainfall (mm)	Duration (yrs)	Dominant pasture species	Trial technique	Rates of N (kg/ha)	Pasture production responses	Reference(s)
Woodville	Brown	Range of hill aspects and slopes	504 (Aug – Nov)	0.33 (Aug – Nov)	Browntop/sweet vernal	Paired paddocks with exclusion cages	0, 58	Significant ($P<0.05$) from all aspects and slopes (average 25 kg DM/kg N) with greatest efficiency (38 kg DM/kg N) from NW steep site	Ball et al. (1976)
Woodville	Brown	NE and SW aspects – 10–15° slope	1100	Spring and autumn applications	Ryegrass/browntop/sweet vernal, crested dogstall	Small plot mowing	0, 10, 20, 40, 80, 160	At lower N rates efficiencies of 10–25 kg DM/kg N At higher N rates efficiencies of 5–7 kg DM/kg N Greater responses from SW cf NE aspect	Luscombe (1979)
Woodville	Brown	Mainly east and north aspects – easy to steep hill country	1100	3	Browntop/sweet vernal/dogstall/ryegrass/white clover	Grazed farmlets with exclusion cages	0, 37 – 50	At soil Olsen P 15 – average of 26 kg DM/kg N At soil Olsen P 8 – average of 29 kg DM/kg N	Lambert & Clark (1985)
Poverty Bay (6 sites)	Brown	Flat to rolling		1 – 2 spring, autumn and winter applications	Ryegrass/browntop/Yorkshire fog	Small plot mowing	0, 25, 50, 100	Efficiency of response decreased from 10 to 8 kg DM/kg N from 25 to 100 kg N/ha Efficiency of response was July>June>August>September>April>March>May	Korte (1988)
Woodville	Brown	Easy hill	1100	2	Browntop/sweet vernal/dogstall	Sheep grazing with exclusion cages	400 kg N/ha/yr in 8 applications	22, 19 and 18 kg DM/kg N under low, medium and high soil Olsen P levels	Lambert et al. (2003)
Hawke's Bay/Wairarapa (5 sites)	Pallic and Pumice	Flat to steep hill	826 - 1348	Early spring applications for 3 years	Browntop/ryegrass/subterranean and white clover	Small plot mowing	0, 30, 60, 90	Flat to easy slopes – significant ($P<0.05$) increases for all sites in spring, significant depressions ($P<0.05$) at two of these sites in summer/autumn Easy to steep slopes – significant ($P<0.05$) increases for all sites in spring	Gillingham et al. (2007) Gillingham et al. (2008)
Waipawa	Pallic	Easy to steep hill	800	Winter applications over 6 yrs	Browntop/ryegrass/subterranean and white clover	Sheep and cattle grazing with exclusion cages	0, 30	Significant effects ($P<0.05$) of aspect and slope North easy 17 kg DM/kg N, South easy 8 kg DM/kg N, North steep 47 kg DM/kg N, North easy 23 kg DM/kg N	Gillingham et al. (2003)
Woodville	Brown	S aspect – 12–25° slopes	1100	Aug–May applications over 3 yrs	Browntop/ryegrass/sweet vernal/dogstall	Large plots with exclusion cages	0, 100, 200, 300, 400, 500, 750	Annual pasture production ranged from 11 to 16 t DM/ha from 0 to 750 kg N/ha/yr	Hoogendoorn et al. (2017)

Table 6 Pasture and animal production responses to lime.

Location	Soil order	Topography	Annual rain-fall (mm)	Duration (yrs)	Trial technique	Initial soil pH	Rates of lime (t/ha)	Response in pasture production	Response in animal production	Reference(s)
East Coast/ Poverty Bay (8 sites)	Brown, Allophanic and Pumice	Hill	1540 – 1980	2	Small plot mowing	5.3 – 5.8	0, 1.25, 2.5, 5	Significant (P<0.05) at 2 sites with pH 5.3 and 5.4		O'Connor & Gray (1984)
Masterton	Pallic	Flat	900	5	Small paddocks with exclusion cages	5.3	0, 6.3	Significant (P<0.05)	Significant increase (P<0.05) in lamb weaning weight at 22 but not 15 SU/ha	Bircham & Crouchley (1976, 1977)
Hastings	Pallic	Flat	800	6	Small paddocks with exclusion cages	5.4	0, 0.2/yr, 7.5	Significant (P<0.05) to 7.5 t lime/ha for 3 years		Morton et al. (1998)
Waipawa (4 sites)	Pallic	South and north aspects – easy and steep slopes	800	3	Small plot mowing	5.4 – 5.6	0, 0.5, 1, 2, 4, 8	North easy – non-significant response North steep – significant (P<0.05) up to 1 t lime/ha in Yr 2 South easy – significant (P<0.05) up to 1 t/ha in Yrs 2 and 3 South steep – significant (P<0.05) up to 1 t/ha in Yrs 2 and 3		Morton et al. (2005)

the ranges of 30–40 kg S/ha/yr for Sedimentary and 40–50 kg S/ha/yr for Pumice soils required to overcome a S deficiency (Morton & Roberts 2016). As indicated by the results from two of the S response trials, elemental S with particle size of less than 0.5 mm should be added to autumn fertiliser applications so that there is sufficient S supply for the next spring.

- There was no consistent relationship between soil QTK levels and response in pasture production to applied K in the regional trials but soil QTK levels were 6 or below at the four sites where a response was measured. These results are consistent with the recommendation for the soil QTK levels that will sustain near-maximum pasture production being 5–8 for Sedimentary soils and 7–10 for Pumice soils (Morton & Roberts 2016). However, variability between sites means that clover vigour and K content should be observed and measured to determine whether or not fertiliser K is required. The longer-term trials showed no consistent response so maintenance K rates could not be determined but national trial results suggest a requirement of 6–28 kg K/ha/yr as stocking rate increases from 7–13 SU/ha that decreases with greater soil supply of K (Morton & Roberts 2016).
- All pastoral soils have limited N supply for pasture growth so the significant pasture production responses to N fertiliser were to be expected. Application rates of 20–40 kg N/ha were included as treatments in most of the regional trials and this range was subsequently recommended by Morton and Roberts (2016) to maximise pasture response as it had been derived from a range of N response trials across various regions. Application of N can be a profitable option to increase pasture production especially if applied in late winter to increase feed supply for multi-lambing ewes and finishing cattle. Differential aerial application of N to sunny, steep slopes with less legume was shown to result in a greater response than from shady or easy slopes.
- The regional lime trials measured a significant response in pasture production to lime when initial soil pH was 5.3–5.4, which is consistent with results from a North Island database of lime trial results (Edmeades et al. 1984). On hill country, lime should be applied to maintain soil pH in the range of 5.4–5.6 with the best policy to aerially apply lime at 0.5 to 1 t/ha to 10–20% of the farm every year (Morton et al. 2019). If lime can be ground-applied then soil pH should

be maintained at 5.8–6.0 (Edmeades et al. 1984).

6. As shown by results from national trials (e.g. Morton & Morrison 1997), Mo can be required if clover Mo content is below 0.1–0.2 ppm and clover N content below 4.5%.

The main knowledge gap highlighted by this review was the need for more longer-term K response trials, especially on hill country and preferably under grazing on Pallic soils that contain larger amounts of non-exchangeable soil K that can supply K to the pasture. Although there is a relative lack of research for S requirements, S is the lowest cost nutrient to apply, is included in superphosphate anyway and it is difficult to find S-responsive trial sites.

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