Intensive pH sampling and variable rate surface application of lime: does it pay?

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Abstract

The principles of production economics were used to generate profit-maximising lime 'prescriptions' for each homogenous zone (HZ) within 10 case-study cropping paddocks in the Victorian HRZ, and to quantify the net benefits of the precision liming strategy.

The initial pH_{ca} distribution within each paddock was obtained using intensive point sampling at the rate of two soil cores per hectare followed by spatial interpolation to a resolution of 10 square metres. The method used to determine the lime rates for each HZ zone involved optimisation, simulation and accommodating the dynamic nature of the acidity of the soil.

The expected payoff from the precision strategy was positive for all 10 paddocks. It was shown to depend mostly on the physical attributes of the soil (i.e. in-paddock pH variation and buffering capacity). Net benefits increased substantially as pH_{ca} fell from about 5.0 to 4.2. Productivity gains due to increased yield were most important in determining the size of the benefits and more than offset the additional costs.

If farmers plan to grow acid tolerant crops and have a relatively homogeneous paddock (CV less than 5%), then they need not worry unduly about the most appropriate method (precision or traditional) for applying lime. But if they want the option of planting high value, acid sensitive crops such as pulses, and if the in-paddock variation in pH exceeds 5%, then it pays to pursue a profit-maximising precision strategy involving intensive pH sampling and variable rate surface application.

Key Words: variable rate lime application, lime prescription maps, high rainfall cropping, decision making, optimisation

Introduction

Soil acidification is a cost of productive agricultural systems - whether from nitrogen fixation by legumes in mixed pastures or crop rotations, or from the increased use of nitrogen fertilisers. It affects at least 5.5 million hectares (50%) of Victoria's agricultural land and looms as a major soil degradation issue (NHT 2001).

Land degradation problems arising from induced acidification are mostly reversible by applying lime. ABS data show the average rate of application of lime is only about 1.5 t/ha, which is considerably less than the general minimum recommendations of 2.5-7.5 t/ha. Moreover, few Victorian farmers, about 1,000 (5%) use variable rate application (ABS 2018). Variable rate application is used to apply a wide range of agricultural chemicals, lime being only one of many; and no statistics are available on the application of variable rate technology to managing soil acidity. However, service providers supporting variable rate liming are increasingly active.

Agriculture Victoria Research (AVR) is conducting a study on 10 case-study paddocks in the HRZ of Victoria to demonstrate the benefits of using intensive point sampling of surface soil pH and the precision application of lime in intensive cropping systems. The economic analysis of the experimental results reported in this paper follows the best-practice method described by Mullen (2001). It involves optimisation, simulation and accommodates the dynamic nature of the acidity nature of the soil - in that production in the current period is affected by current pH and in turn has an impact on next period's pH. It uses Palisade's (2019) Evolver for deterministic optimisation and RISKOptimizer for sensitivity analysis.

Research Questions

The research questions were:

Q1: What are the net benefits of gathering information on the pH distribution of a paddock using intensive point sampling AND variable rate application (VRA) of lime? This practice is called the 'precision strategy'. The precision strategy assumes the producer has 'complete' knowledge about the pH levels and locations within a paddock and varies the rate of lime throughout the paddock according to the various pH measurements.

Q2: What are the net benefits of VR application compared to uniform application once detailed information has been obtained about the pH distribution within the paddock? The 'uniform' strategy assumes the producer continues to have 'complete' knowledge of the pH levels and locations within a paddock but then applies a single rate of lime.

Q3: How do the precision and uniform strategies compare to the traditional approach for determining how much lime to apply to an acid paddock? The traditional approach relies on one composite sample of 30 cores taken from random within a paddock to trigger a decision to put on lime at a blanket or uniform rate. The rate applied is enough to raise the pH_{ca} of the paddock to a target of 5.2 (Agriculture Victoria, 2019).

Hypotheses

Our hypothesis, based on previous research summarised by Mullen (2001), is that it is profitable to use intensive sampling and VRA of lime to manipulate soil acidity in cropping systems.

However, it is not clear that VRA is economically superior to the uniform strategy; nor that either are superior to the traditional approach.

Pannell (2006) has argued that, production plans that represent a maximum profit or optimum method are surrounded by a host of variations that generate very similar results. The jargon is that ‘payoff functions are flat’, meaning there are many ways to run a farm system to achieve similar outcomes, close to best. This is, in part, a result of the operation of the law of diminishing returns to extra inputs. This principle also applies to extra inputs of information to production decisions, as demonstrated for liming by O’Connell *et al.* (1999). It led Pannell (2006) to surmise that using precision farming technologies to fine-tune applications of variable inputs might not be of much benefit to farmers. Rogers *et al.* (2016) question Pannell’s conclusion pointing out O’Connell *et al.* (1999) used a whole-field pay-off function. They then demonstrated a high degree of variability in relative curvature of pay-off functions for applied nitrogen for different homogenous zones (HZs) within the same field. The results imply that targeting input use optimally at the level of the HZ can be important for profitability, even in cases when a whole-field analysis would suggest that optimality of input use is not warranted.

Method

10 case-study paddocks

Initial in-paddock pH_{ca} distributions were obtained for 10 case-study paddocks in the HRZ of Victoria. Four of these were in the south-west, three in the north-east and two in the south-east. (figure 1).

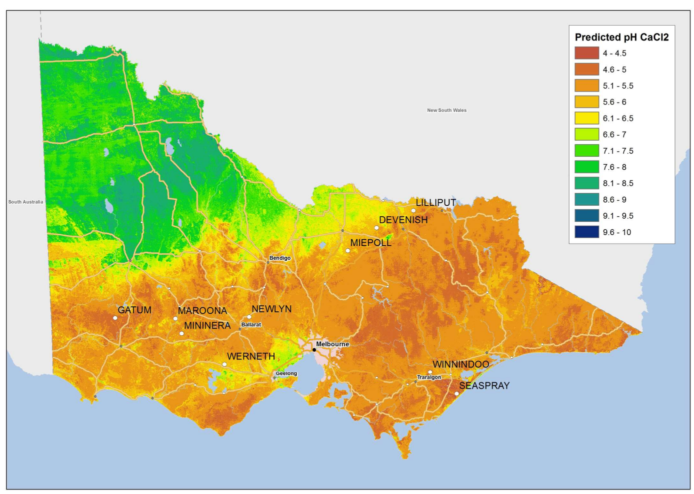

Fig 1. Location of the 10 case-study paddocks in Victoria, Australia.

The pH_{ca} distributions were obtained using intensive point sampling at 100 cores per paddock, with 76 in a grid and the remaining 24 shared between three clusters, followed by spatial interpolation to a resolution of 10 square metres. The width of lime spread by a commercial spreader is in the range of 10 to 14 m. Therefore, kriging to 10m is a practical smallest spatial unit.

Attributes of the top-soil of the 10 paddocks are contained in Table 1. The case-study paddocks comprise mostly clay loam soils with a total organic carbon content around 3%. The buffer capacity of the soil (pH BC), a reasonable determinant of the pH response to added lime, was predicted using the pedotransfer function of Aitken *et al.* (1990). All paddocks had a relatively high pH BC of about 4-5t $CaCO_3$/ha per unit pH_{ca}. All paddocks were acidic, but the variability in pH, as measured by the coefficient of variation (CV), was low compared to the average of 5% observed by commercial operators (Kirsten Barlow *pers. comm.*). For this reason, hypothetical pH_{ca} distributions based on the normal distribution but with higher CVs were also examined in a threshold analysis for the Newlyn site.

Table 1. Selected attributes of the 10 case-study paddocks

Region	**Location**	**Size (ha)**	**Clay content (%)**	**Total organic carbon (%)**	**pH buffer capacity ($tCaCO_3$/ha/unit pH)**	**pH_{ca}[1]**	**CV pH_{ca}[1] (%)**
Gippsland	Seaspray	112	12	3.4	4.63	4.22	2.1
	Winnindoo	40	22	3.0	4.01	4.57	1.4
North East[2]	Miepoll	134	29	3.5	4.53	4.78	1.4
	Devenish	37	22	3.5	4.63	4.96	3.8
	Lilliput	28	22	3.5	4.63	4.84	2.1
Central Highlands	Maroona	31	12	3.7	5.02	4.81	3.6
	Newlyn	12	29	3.9	5.01	4.87	3.7
South West	Werneth	49	22	2.5	3.40	4.98	5.0
	Mininera	108	18	3.5	4.69	4.97	2.5
	Gatum	45	17	3.5	4.69	4.97	2.2

1. *Of the interpolated data*
2. *Clay content and organic carbon content are preliminary based on expert opinion*

Discounted cash flow model

A summary of the general process and data requirements used to solve the DCF model for the VR strategy in single year are shown in figure 2.

Lime application rates for each HZ (box b) were determined using profit-maximising principles. These rates can be displayed as frequency distributions or presented spatially as prescription maps. The decision rule was to apply lime to maximise the expected discounted stream of future benefits less discounted stream of future cost (i.e. the Net Present Value, or NPV) over a 10-year time horizon (box i).

Lime rates were limited to 5 t/ha to avoid adverse effects of boron deficiency and were in 0.5 t increments between 0.5 and 5 t/ha. 'Maintenance' applications of lime were not accommodated in the DCF model. Rather, a single application occurs in year one of a 10-year planning horizon; should predicted pH_{ca} fall below a desired level then a new liming decision can be made at that time.

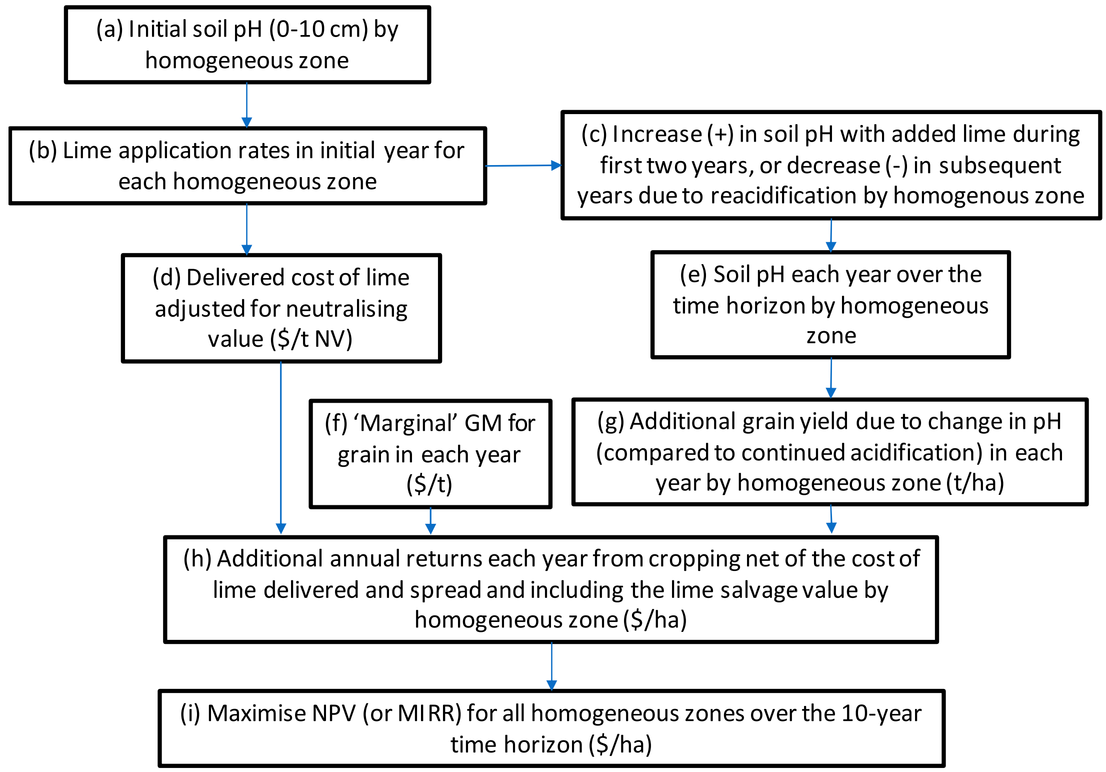

Fig 2. Flow chart depicting the process of solving the DCF model for variable-rate application for a single period.

Economic optimisation requires response function by crop type (box g) and other technical relationships relating to the change in pH over time with and without added lime (box c). These were obtained from conventional field experiments supplemented by information from the scientific literature.

Cropping scenarios examined were based on rotations commonly used by croppers in the study area and include both acid-sensitive and acid-tolerant crops. Increasing soil acidity would be accompanied by changes from acid-sensitive to acid-tolerant species/cultivars in crop rotations. Other methods for countering soil acidity such as the adoption of more nitrogen efficient and less acidifying agricultural practices were not considered.

The counterfactual against which additional crop returns due to liming were evaluated (box h) was the yield with no added lime, i.e. continued acidification of the paddock.

The risky outputs were the NPV and the modified internal rate of return (MIRR), the former was evaluated at a real discount rate (r) of 7.6% p.a. (10% nominal) – a level which includes a modest risk premium (the 'risk-free' rates of return in the economy being in the range 3-5%). Risky inputs were crop prices and yield potential, which were defined by probability distributions.

Soil technical relationships

Soils have an intrinsic ability to resist pH change—either a decrease from an acid input (acidification) or an increase from the application of lime. This is known as the pH buffer capacity (pH BC) of the soil.

Important technical relationships built into the DCF model depend on the buffer capacity of the soil, these being (a) the pH response to added lime, (b) the acidification rate and (c) the residual value of added lime. These relationships are linear over the range pH_{ca} 4.2 to around pH_{ca} 6.5. Outside this range soil is increasingly very strongly buffered by precipitation-dissolution reactions involving carbonate minerals at high pH and aluminium hydrous oxides at low pH. In these soils, acid addition causes little pH change (Helyar and Porter 1989).

Measurements of the buffer capacity of the soil are seldom made, so an estimate was made based on the pedotransfer function of Aitken *et al.* (1990) (equation 1). According to NHT (2001 p131), this equation is the best predictor of the pH BC (accounting for 70% to 90% of the variance) for a wide range of surface soils (0-10 cm).

$$\text{pH BC} = (0.955\ \text{OC\%} + 0.011\ \text{Clay\%}) \times \text{BD} \quad (1)$$

A higher organic matter (OC%) or clay content (Clay%) will result in a higher pH buffering capacity (figure 3). The relationship is expressed as tonnes of lime required to change the pH by one unit per hectare for a surface soil with a given bulk density (BD).

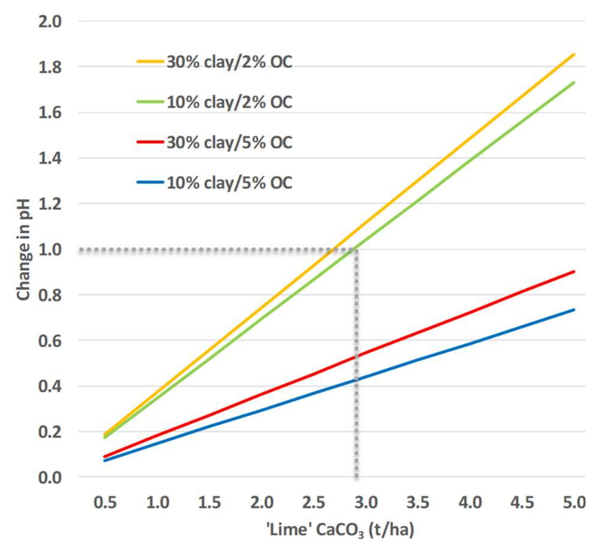

Fig 3. Predicted relationships between the lime required to change pH (estimate of pH buffering capacity) on soils with varying soil organic carbon and clay contents (after NLWRA (2001) p131.

The magnitude of the change (increase) in soil pH_{ca} with added lime (ΔpH_{ca}), sometimes called the 'soil factor', depends on the amount of lime applied (LR) and was calculated as:

$$\Delta pH = LR / \text{pH BC}. \quad (2)$$

Application of liming materials to surface soils to alleviate soil acidity takes 2-3 years to have full impact (Miller, 2017a). Liming does not stop soil acidification. Rather soils reacidify at the new soil pH level, and over time, surface-applied lime slowly exerts its effect at lower soil depths. The change in pH over the first two years was determined by equation 3 (Lukin and Epplin, 2003).

$$pH_t = pH_{t=0} + bt^{\alpha} e^{\beta t} \quad (3)$$

where b is ΔpH_{ca} from equation 2; α is the rate of increase in pH_{ca}, and β is the rate of decrease in pH_{ca}. To achieve the 2-year lag, α was set to 0.64, and β to -0.22 (both determined using Excel's solver).

Annual rates of acid addition or load (L) vary with the type of farming system and seasonal conditions (seasonal conditions affect the extent of nitrate leaching, a major factor in soil acidification) (NHT 2001). Rates of acid addition are conventionally expressed as lime needed to neutralise the acid load generated each year (kg lime/ha/year). Rates of acidification expressed in terms of units of pH_{ca} per year are determined as follows:

$$\Delta pH = L / 1000 / pH\ BC \quad (4)$$

The annual acid load could be approximated using the Helyar-Porter method (Helyar and Porter 1989) and Agriculture Victoria's on-line 'tools' (Agriculture Victoria 2019). However there are so many unknowns in this calculation, that it's considered best to infer the annual acid load from published rates informed by acidification rates observed in field trials (Lisa Miller *pers. comm.*). The cropping system is assumed to be moderately acidifying with annual acid load of 110 kg/ha $CaCO_3$ equivalents, consistent with acidification rates observed in local field trials (Miller 2018).

The residual value (RV) of 'unused' lime stored in the soil at the end of the planning horizon was calculated as in equation 5:

$$RV = [(pH_{t=n} - pH_{t=0}) \times pH\ BC] / (1+r)^n \quad (5)$$

Crop technical relationships

Two crop rotation scenarios dominated by intensive cereal production (barley, canola and wheat) were examined. The first included more acid tolerant crops (BWCWW). The second included a high value (table 3) but acid-sensitive pulse, namely faba beans (BPCWW).

The yield potential (at 100% relative yield) for each crop is the water limited yield in the Victorian HRZ (table 3). The relative yield (Y_r) was predicted by equation 6 from the Optlime tool (Gazey 2008). Parameter values for each crop type (table 2) were chosen to match SFS trial results as reported in Miller (2017b).

$$Y_r = 1 - e^{(-\gamma * \max(0,\, pH - \delta))} \quad (6)$$

Table 2. Coefficients used to model the relative yield responses to soil pH

Crop	γ	δ
wheat	3.8	3.6
canola	2.3	3.7
barley	2.3	3.8
pulse	1.4	3.9

Figure 4 shows that the yield response steepens for all crop types as pH_{ca} approaches 4.2. Conversely, as pH_{ca} increases above 4.8 the curves start to flatten out – except for faba beans (and many other grain legumes) that have rhizobia highly sensitive to acidity and require higher pH_{ca} levels. The SFS trials show that yields for faba beans drop yield 20% lower at pH_{ca} 4.8. Barley is also considered acid sensitive and the yield at pH_{ca} 4.2 dropped by 34%. Canola is considered acid sensitive, and the SFS trials indicate possibly a 15% reduction in yield at surface pH_{ca} 4.4. Wheat is considered tolerant of acidity but a pH_{ca} of 4.5 appears to reduce yields by 5% to 10%.

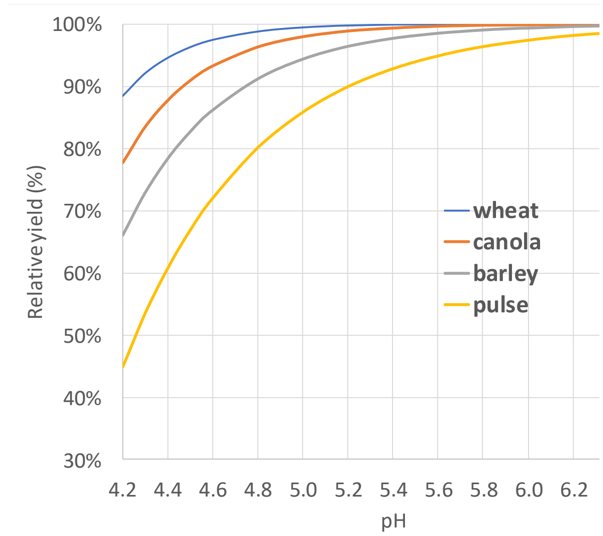

Fig 4. Relative yield by crop type calibrated to SFS trial results

'Marginal' gross margins for cropping rotations

Absolute yields and gross crop returns were achieved by multiplying Y_r by the average of water-limited yields (Y_{max}) and the crop unit price (P) (table 3). Water-limited yields were averages for the five years ending 2016 and were sourced from either CSIRO (2018) (canola and barley) or Nigussie *et al.* (2018) (wheat and faba beans). Prices were 5-year averages from GRDC (2018). Accounting for costs that vary with yield, the marginal GM for the acid tolerant rotation was $270/t (on average), and the marginal GM for the acid sensitive rotation was $300/t (on average).

Table 3. Expected yields and 'marginal' gross margins by crop type

	Distribution type	Wheat	Canola	Barley	Faba beans
Water limited yield (t/ha)	Uniform. MAX = 5 y.a. MIN = 15% discount on modelled/ experimental yields.	3.7-4.3 $\mu = 4.0$	3.2-3.7 $\mu = 3.4$	4.6-5.4 $\mu = 5.0$	3.5-4.2 $\mu = 3.8$
Price ($/t)	Normal truncated at 5% and 95% percentiles based on 5 years' data.	$\mu = 270$ $\sigma = 31$	$\mu = 512$ $\sigma = 30$	$\mu = 265$ $\sigma = 42$	$\mu = 442$ $\sigma = 115$
Variable costs ($/t)	Point values from gross margin budget guide.				
- levies		2.75	5.22	2.70	4.51
- insurance		0.03	0.05	0.03	0.04
- harvest		25	25	25	25
- freight		20	20	20	20

Farm-gate price (net) ($/t)	Point values (5y.a. from gross margin budget guide)	222	462	217	392

Costs for the precision strategy

To avoid complications due to the scale of operations (Malcolm *et al.* 2005, p 104), costs for the precision strategy (table 4) were based on contract rates. Mapping costs were commercial rates of $14/ha adjusted for bundled testing costs (Precision Agriculture *pers. comm.*). VR spreading costs $16/ha and commands an additional $4/ha over uniform application ($14/ha) (Dellavedova Fertiliser Services, *pers. comm.*).

Testing costs for the intensive point sampling used in this AVR study assumes 2 cores/ha costed at $18/sample (Nutrient Advantage, 2018). Lime costs (delivered and spread) assumed a neutralising value (NV), the most important value determining attribute for lime, of 90%. Transport costs, a major portion of the total, assumed a distance of 250km (GRDC, 2018).

Total costs amounted to about $200/ha @ 100% NV (assuming lime is spread @ 2.5t/ha).

Table 4. Costs for the precision strategy

Item	$/ha	$/ha @ 100% NV	$/t @ 90% NV	$/t @ 100% NV
Mapping and soil testing costs	**43**	**43**		
- pH mapping	7	7		
- Laboratory analysis of soil samples (2 top-soil samples /ha @ $18 each)	36	36		
Lime delivered			**42**	**47**
- Price at source			22	24
- Freight 250 km @ 0.08 $/km/t			20	23
VR spreading (surface application)	**16**	**18**		

Results

Payoff from VR liming strategy informed by intensive point sampling

The payoff from the VR liming strategy varied with the physical attributes of the soil, i.e. the average pH_{ca} levels and in-paddock variation, as measured by the CV (figure 5d).

For the cropping scenario involving the more acid tolerant crops (BWCWW) liming of all paddocks met the required return on capital of 10% p.a (nominal). Net benefits increased rapidly as the paddock-average pH_{ca} declined. The NPV ranged from $12/ha/yr for the paddock at Mininera (with an average pH_{ca} of 5.0 and CV of 2.5%) to $199/ha/yr for the paddock at Seaspray (with an average pH_{ca} of 4.1 and CV of 2.1%). The NPV was also boosted as spatial variation increased within the paddock; being $27/ha/yr for the paddock at Werneth that had a CV of 5.0%, but a relatively high average pH_{ca} of 5.0.

Financial feasibility was determined using the pay-back period. Reflecting the relative profitability of adding lime to the case-study paddocks, the payback period ranged from 1 year to 6 years (figure 5f).

Liming costs had a material effect on net benefits (figure 5a and 5b). However, productivity gains due to increased yield (figure 5c) were more important in determining differences in the size of the net benefits between case-study paddocks

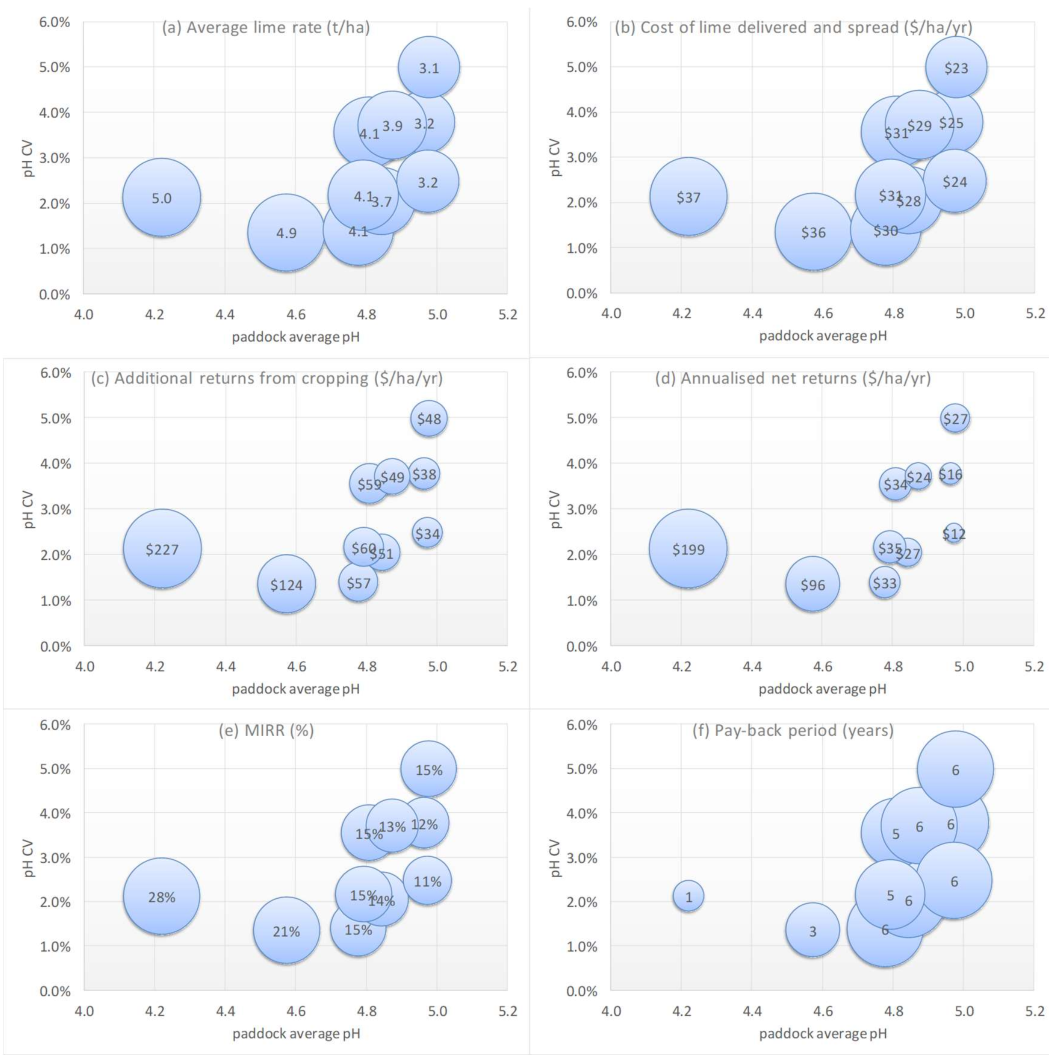

Fig 5. Change in the (a) average lime rate, (b) lime cost, (c) returns from cropping and (d) annualised net returns (e) MIRR and (f) pay-back period with the pH

These findings suggest that net benefits would be very sensitive to assumptions about crop types in the rotation (acid tolerant v acid sensitive), and crop prices and yield potential over the planning horizon (risky variables in the analysis).

This is demonstrated in figure 6 with reference to the paddock at Newlyn which has an average pH_{ca} of 4.9 and CV of 3.7%. Net benefits for an acid tolerant crop rotation were positive at the specified discount rate, averaging $18/ha/yr in the range $11 to $22 ha/yr. Benefits were substantially greater and more variable if the crop rotation included an acid-sensitive crop such as faba beans (BPCWW).

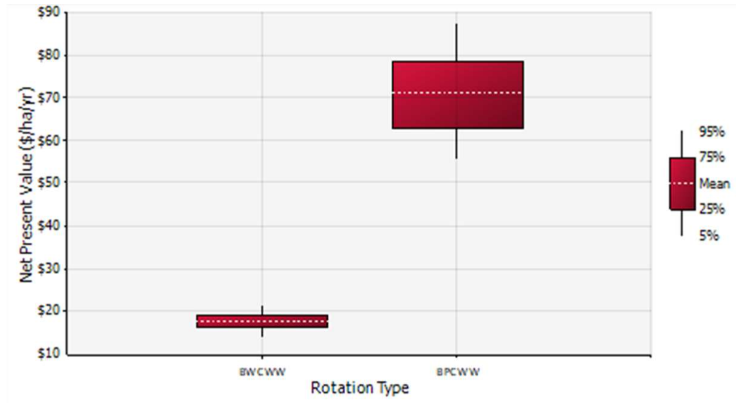

Fig 6. Range in annualised net benefits at Newlyn for variable rate application of lime by rotation type

Payoff compared to uniform application and traditional strategies

VRA was more profitable than uniform application in only one instance (Werneth), as savings in the delivered cost of lime were typically offset by the additional costs of variable rate application (table 5). The VRA strategy was on average 32c less attractive on a per hectare per year basis than the uniform strategy, equivalent to about 10% of the annualised $2.60/ha contract rate for variable rate application.

The lack of clear benefits from VRA can be attributed to the low variability in pH within the case-study paddocks. For an acid tolerant crop rotation on the Newlyn paddock, the CV would need to lift above about 5.0% for the additional benefits of VR liming *per se* to become positive (figure 7). The benefits increased rapidly as the in-paddock variability increased.

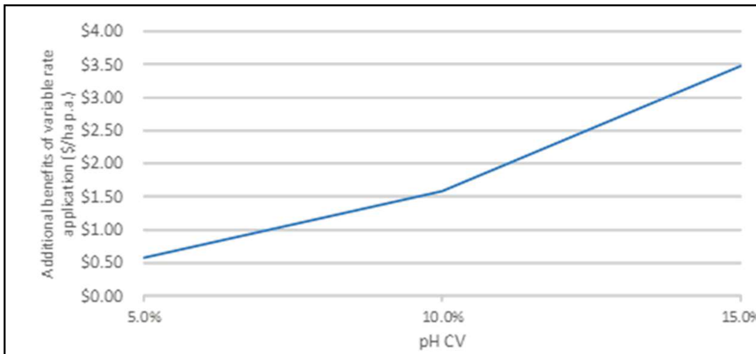

Fig 7. Additional benefits of variable rate application (compared to uniform rate) at Newlyn for hypothetical increases in pH variability ($/ha/yr)

The robustness of the traditional strategy is also shown in table 5, as the traditional strategy was superior to the uniform strategy on half the case-study paddocks. Benefits form increased yields were lower for the traditional strategy, as lime rates required to achieve the 5.2 target were lower (typically in the range 1 to 2.5 t/ha); but so too were the costs of lime delivery and spreading, and other costs associated with sampling and testing.

Table 5. Net benefits by liming strategy ($/ha/yr)

Case-study paddock	Net benefits of VR strategy	Net benefits of uniform strategy	Savings in lime costs (delivered) (+)	Additional application costs (-)	Additional gains from VR application?	Net benefits of traditional strategy	Additional gains compared to traditional strategy?
Seaspray	199.18	199.83	0.00	-0.65	no	202.53	no
Winnindoo	96.45	97.03	0.53	-0.65	no	94.61	yes
Miepoll	32.53	33.07	-0.53	-0.65	no	33.95	no
Devenish	16.10	16.12	1.97	-0.65	no	17.45	no
Lilliput	27.20	27.65	2.04	-0.65	no	29.29	no
Maroona	34.41	34.51	2.41	-0.65	no	33.88	yes
Newlyn	24.48	24.55	0.74	-0.65	no	23.56	yes
Werneth	27.15	27.01	-0.05	-0.57	yes	23.84	yes
Mininera	12.04	12.56	2.28	-0.64	no	11.56	yes
Gatum	34.90	35.27	-0.56	-0.65	no	35.31	no

Conclusions

Reaping the benefits of the precision strategy for an input such as lime is difficult, because benefits depend on the decisions made by farmers and their advisors based on a high level of data collection and management, interpretation, and judgement. The DCF model described in this paper demonstrates the nature of the data, analysis and interpretation involved in the decision-making process.

If farmers plan to grow acid tolerant crops and have a relatively homogeneous paddock (CV less than 5%), then they need not worry unduly about the most appropriate method for applying lime. On only half our case-study paddocks were the precision (variable rate or uniform) strategies more profitable than the traditional approach. The net benefits of VR liming exceeded those from uniform liming only for the one site where the in-paddock pH variation was 5%. If farmers want the option of planting high value, acid sensitive crops such as pulses, and if the in-paddock variation in pH exceeds 5%, then it pays to pursue a profit-maximising precision strategy.

Whether a paddock under consideration has very considerable variability is not known in advance of testing. A situation faced by researchers as well as farmers.

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