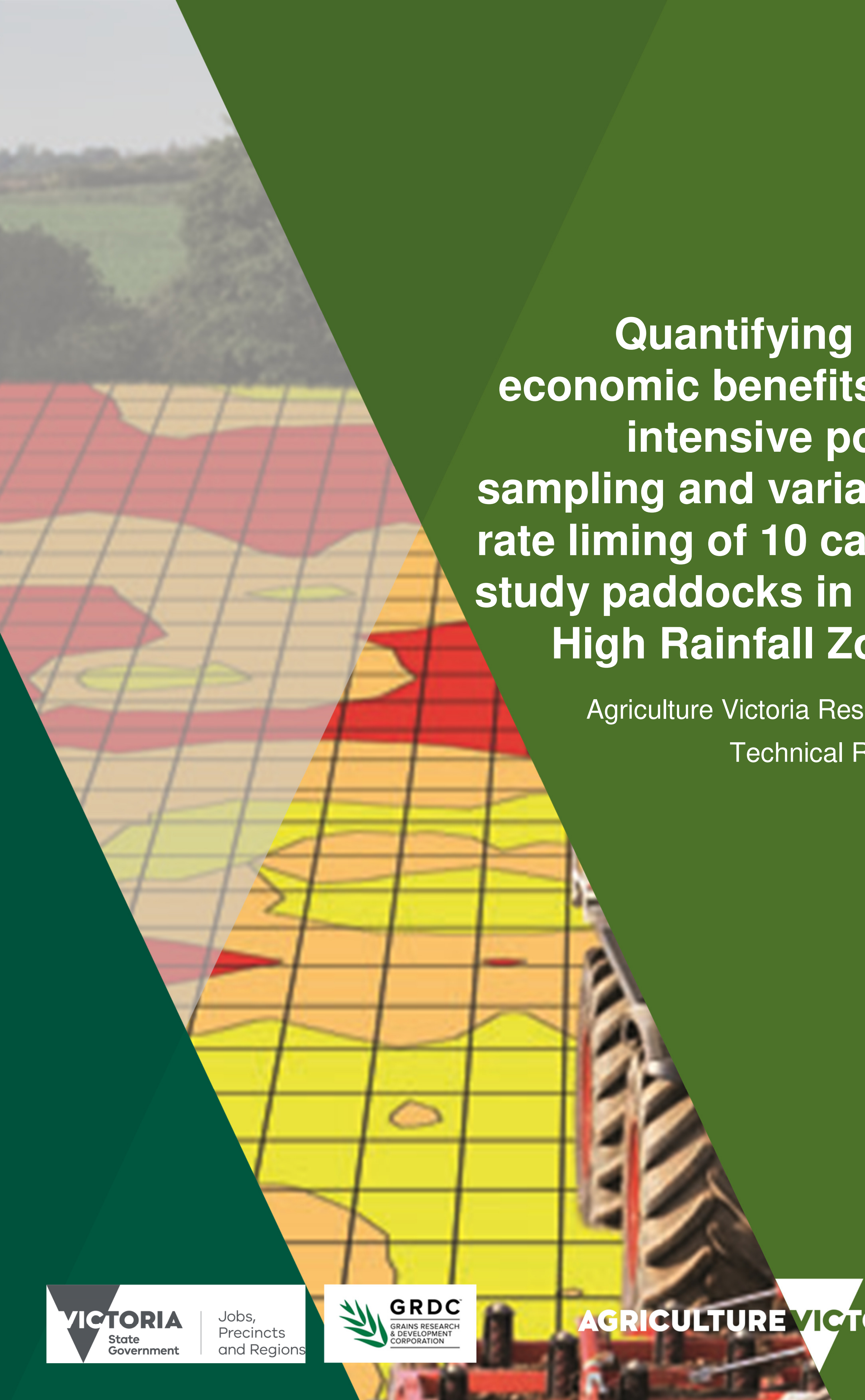

Quantifying the economic benefits of intensive point sampling and variable rate liming of 10 case-study paddocks in the High Rainfall Zone

Agriculture Victoria Research

Technical Report

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AGRICULTURE VICTORIA

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Contents

EXECUTIVE SUMMARY

Soil acidity affects up to 5.5 million hectares (50%) of Victoria's agricultural land and soil acidification looms as a major soil degradation issue (NHT 2001). Soil acidification can be seen is a cost of productive agricultural systems - whether from product removal, increased potential for nitrate leaching, the build-up of soil organic acids, or from the increased use of nitrogen fertilizers.

Soil acidity and acidification are mostly ameliorated by applying agricultural lime. Australian Bureau of Statistics (2018) survey 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 (Agriculture Victoria 2019). Moreover, few Victorian farmers, about 1,000 (5%), use variable rate application. Variable rate application is used to apply a wide range of agricultural chemicals, lime being only one of many, so that the application rate is adjusted to match changing local requirements within the paddock. No statistics are available on the application of variable rate technology for managing soil acidity, however service providers supporting variable rate liming are increasingly active.

Agriculture Victoria Research (AVR) studied 10 case-study paddocks in the HRZ of Victoria to demonstrate the net economic benefits of using intensive point sampling of surface soil pH and the precision application of lime in cropping systems.

The initial pH_{Ca} distribution within each paddock was obtained by sampling at the rate of 100 soil cores per paddock followed by spatial interpolation to a resolution of 10 square metres.

Discounted cash flow (DCF) analysis was used to generate profit-maximising lime 'prescriptions' for each homogenous pH zone (HZ) within the 10 case-study cropping paddocks, and to quantify the net benefits of the precision liming strategy. These benefits were compared to alternative liming strategies, including traditional approaches and uniform application. The analysis followed the best-practice method described by Mullen (2001). It involved optimization and simulation; and it accommodated the dynamic nature of the acidity nature of the soil, in that production in the current year is affected by current pH and in turn has an impact on pH in the next year.

It was shown that reaping the benefits of the precision liming strategy is difficult, because benefits depend on the decisions made by farmers and their advisors requiring a high level of data collection and management, interpretation, and judgement.

When acid tolerant crops are grown, the net benefits of liming can generally be maximised using low-cost traditional practices. However, if the decision-maker wants the option of planting high-value, acid-sensitive crops then it would pay to pursue a profit-maximising strategy involving intensive point sampling, pH mapping and variable rate application.

The DCF model described in this report demonstrates the nature of the data, analysis and interpretation involved in the decision-making process. The model has been prototyped in MS Excel® and uses Evolver, an optimization add-in that is part of Palisade's DecisionTools Suite. The DCF model is available from the primary author on request and can be used with attribution.

INTRODUCTION

Soil acidity affects up to 5.5 million hectares (50%) of Victoria's agricultural land and soil acidification looms as a major soil degradation issue (NHT 2001). Soil acidification is a cost of productive agricultural systems - whether from product removal, nitrate leaching, the build-up of soil organic acids, or from the increased use of nitrogen fertilizers.

Soil acidity and acidification are mostly ameliorated by applying agricultural lime. Soil testing and liming has traditionally assumed that soil pH varies randomly across a paddock; recommendations on soil sampling for routine testing are based on classic statistics, i.e. collect a composite sample of 30 cores taken at random across a paddock and lime is spread at the one rate across the paddock. The average liming rate in Victoria is about 1.5 t/ha (ABS 2018), which is considerably less than the general minimum recommendations of 2.5 - 7.5 t/ha (Agriculture Victoria 2019).

Few Victorian farmers, about 1,000 (5%) use variable rate application (VRA) for any purpose, liming being only one (ABS 2018). No statistics are available on the application of variable rate (VR) technology to managing soil acidity per se, but data on soil pH variability suggests assuming the paddock is uniform will not always be optimal and risks wasting lime on some areas and under-liming others. Hence service providers supporting VR liming are increasingly active. The average soil pH_{Ca} in 340 grid-sampled paddocks in 2018 taken by Precision Agriculture ranged from 4.18 to 6.25, with the variation within a single paddock (minimum to maximum pH) ranging from 0.1 to 3.2 pH units (Barlow and Stott 2019). Across this data set the coefficient of variation (CV) averaged 4.7% and ranged from 0.7 up to 16%.

The current trend to amalgamate paddocks and farms into one large management unit increases the potential for sub-optimal liming. However, growers have little readily available information on the horizontal and vertical variations in soil pH or the economics of managing spatially variations in soil pH at the paddock scale. Moreover, the potential for regional variations in lime responses and in the variability of soil pH, make it difficult for growers to use information from outside their region. Unsurprisingly, there are many anecdotal instances of little benefit from liming.

In the last 15 years cropping has expanded into the high-rainfall zone (HRZ). In 2014, 1.8 M ha of the Victorian HRZ was cropped with cereals, brassica and legumes. Exactly how much of this land is currently at critical pH levels is not known but all of this area is at risk of acidification due to the nature of cropping systems using higher inputs of ammonium-based N fertilizers, coupled with higher product removal, than in the past.

To help inform decisions regarding VR liming, Agriculture Victoria Research (AVR) studied 10 case-study paddocks in the HRZ of Victoria to demonstrate the net economic benefits of intensive point sampling of surface soil pH and the precision application of lime in intensive cropping systems. The economic analysis was conducted in a whole-farm context and followed the best-practice method described by Mullen (2001). It involved optimization, simulation and accommodated the dynamic nature of soil acidification. It used Palisade's (2019) Evolver for deterministic optimization and RISKOptimizer for sensitivity analysis.

This report documents the method and estimates of the net benefits for each case-study paddock under four soil acidity management scenarios:

- Scenario 1, the 'profit maximising precision' strategy, assumes the producer has a high level of knowledge about the pH levels and locations within a paddock and varies the rate of lime throughout the paddock to maximise profits.
- Scenario 2, the 'profit maximising uniform' strategy, assumes the producer continues to have a high level of knowledge of the pH levels and locations within a paddock but then applies a single rate of lime to maximise profits.
- Scenario 3, the 'target 5.5 precision strategy', assumes that the producer continues to have a high level of knowledge of the pH levels but rather than maximising profits, the decision-maker applies enough lime to raise the pH_{Ca} of the paddock to a target of 5.5.
- Scenario 4, the 'traditional' approach, in which the decision-maker takes one composite sample comprising 30 cores to determine the average pH of the paddock and applies a single rate of lime across the whole paddock sufficient to raise the average pH_{Ca} to a target of 5.5.

Our hypothesis is that it is profitable to use intensive sampling and VR liming 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. In part this is 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).

METHOD

Site description and data collection

Data on within-paddock distribution of soil pH were obtained for ten case-study paddocks in the HRZ of Victoria (figure 1). Five were located in the south-west (Gatum, Maroona, Mininera and Werneth), three were in the north-east (Miepoll, Devenish and Lilliput) and two in the south-east (Winnindoo and Seaspray).

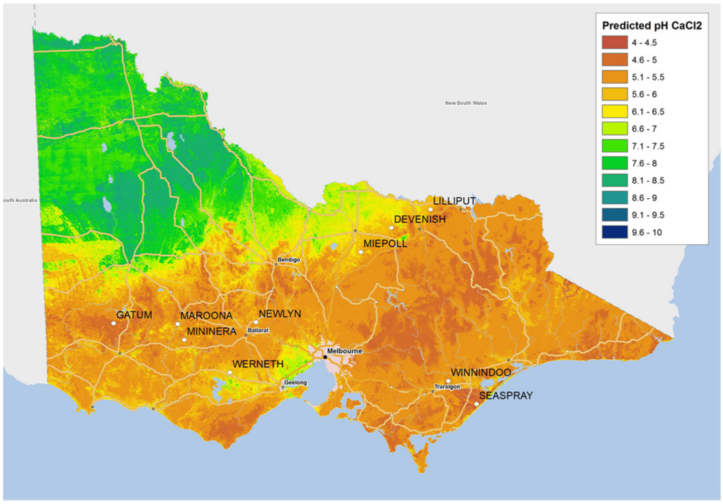

Fig. 1. Location of the 10 case-study paddocks in Victoria.

Spatial soil pH data for each paddock were obtained by intensive point sampling at 100 cores per paddock, with 76 in a grid across the paddock with the remaining 24 shared between three clusters, to observe long- and short-range variability, respectively (figure 2) in accord with Webster and Lark (2013). Interpolated surfaces of soil pH were predicted using ordinary kriging to a resolution of 10 square metres (R - R Development Core Team, 2015). The 10 m resolution was chosen for practical reasons, as it corresponds approximately to the width of lime spread by a commercial spreader. Soil pH (in water and $CaCl_2$) and salinity were determined as described in methods 4A1, 4B4 and 3A1, respectively, from Rayment and Lyons (2011). Determinations were on the air-dried fine earth fraction (<2 mm) from 10 cm sections of each core to the 30 cm depth. Only the data for method 4B4 from the 0-10 cm depth is used here, i.e. pH of soil:0.01 M $CaCl_2$ suspensions at 1:5 ratio (pH_{Ca}). Four cores to 1.2 m deep, were used to describe the soil (McDonald et al., 1990) at each site. Mid-infrared spectroscopy was used to predict total organic carbon and clay content in soil horizons, for predicting soil pH buffering capacity using the model of Aitken *et al.* (1990).

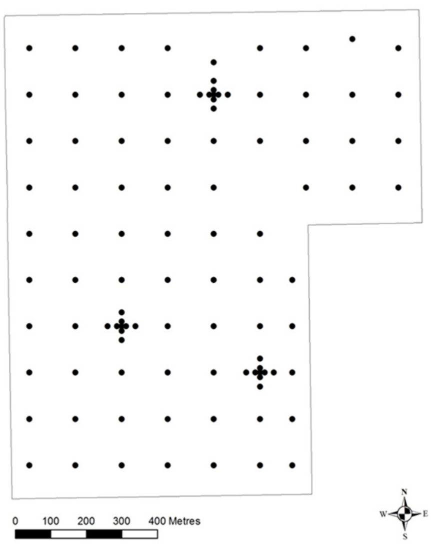

Fig. 2. Sample point map for pH data

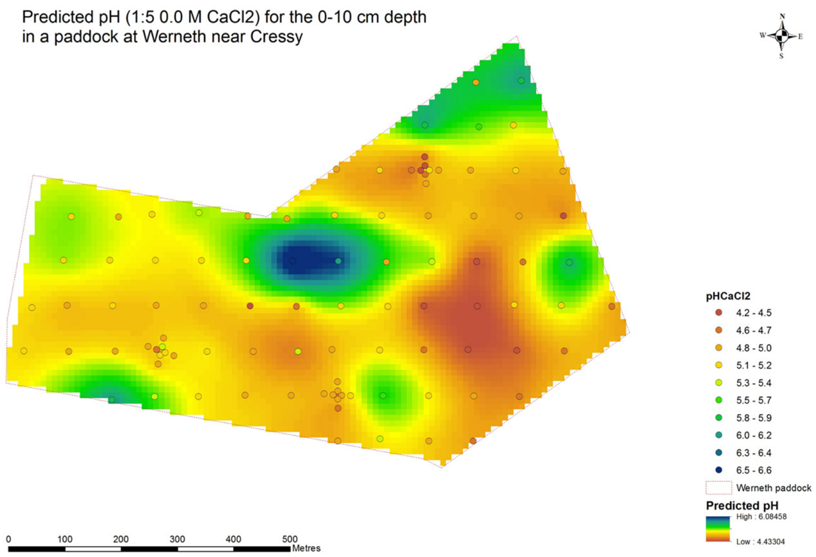

Fig. 3. Interpolated predictions for pH

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Attributes of the top-soil of the 10 paddocks are 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) was predicted using the pedotransfer function of Aitken et al. (1990) from the soil clay content and total organic carbon content. It is a reasonable estimator of the pH response to added lime and from soil acidification. All paddocks had a relatively high pH BC of about 4-5t $CaCO_3$/ha per unit pH_{Ca}.

All paddocks were acidic, with pH_{Ca} ranging from 4.19 at Seaspray to 4.99 at Mininera. The paddocks at Seaspray and Winnindoo were the most homogeneous with the measured standard deviation (SD) 0.2 or less and the coefficient of variation (CV) below the average of about 5% observed by commercial operators. Most paddocks showed considerable variation with SD above 0.3.

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

Location	Size (ha)	Clay content[1] (%)	Total organic carbon[1] (%)	Predicted pH buffer capacity (t $CaCO_3$/ha/unit pH)	Measured pH_{Ca}			Interpolated pH_{Ca}		
					Mean	SD	CV (%)	Mean	SD	CV (%)
Seaspray	112	12	3.4	4.63	4.19	0.20	4.8	4.22	0.09	2.1
Winnindoo	40	22	3.0	4.01	4.55	0.15	3.3	4.57	0.06	1.4
Miepoll	134	29	3.5	4.53	4.80	0.40	8.3	4.78	0.07	1.4
Devenish	37	22	3.5	4.63	4.87	0.37	7.6	4.96	0.19	3.8
Lilliput	28	22	3.5	4.63	4.88	0.58	11.9	4.84	0.10	2.1
Werneth	49	22	2.5	3.40	4.94	0.38	7.7	4.98	0.25	5.0
Mininera	108	18	3.5	4.69	4.99	0.33	6.6	4.97	0.12	2.5
Gatum	45	17	3.5	4.69	4.81	0.40	8.3	4.79	0.10	2.2
Maroona	31	12	3.7	5.02	4.83	0.34	7.0	4.81	0.17	3.6
Newlyn	12	29	3.9	5.01	4.84	0.30	6.2	4.87	0.18	3.7

1. *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 profit-maximising VR strategy in a single year are shown in figure 4. For simplicity, the interpolated pH data was classified into 7 classes representing "homogenous" zones (HZ) of pH in the paddock.

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 (samples of which are contained in Appendices A-J). 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 trace element deficiency and were applied in 0.5 t/ha increments. '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.

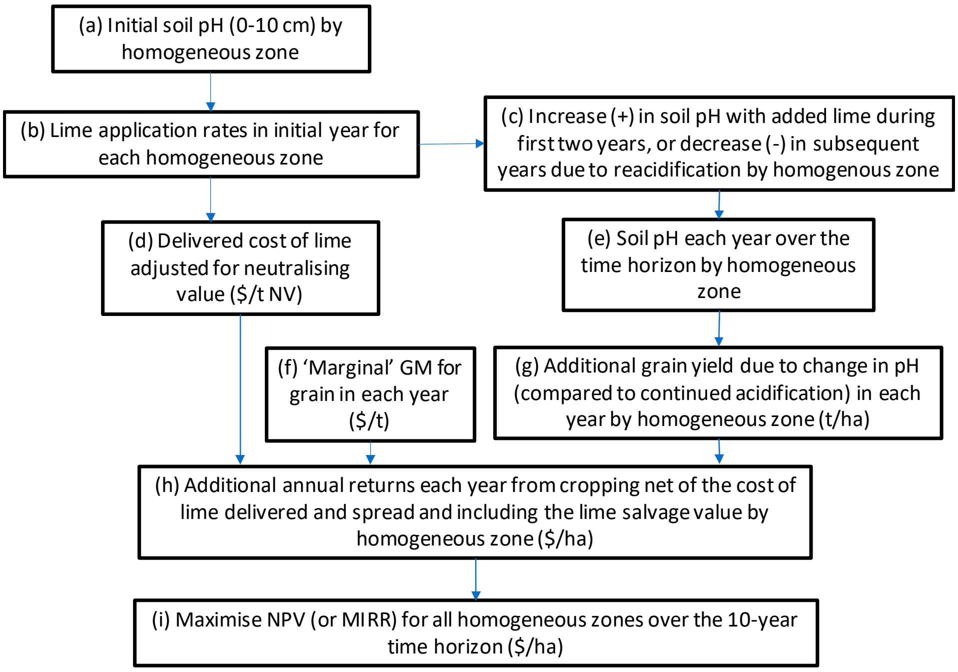

Fig. 4 Flow chart for a single period depicting the process of solving the DCF model for variable rate application of lime

Economic optimization 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. Risky inputs were crop prices and yield potential, which were defined by probability distributions.

Soil technical relationships

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 oxides of aluminium, iron and manganese oxides at low pH. In these extremes, 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).

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

A higher organic matter (OC%) or clay content (Clay%) will result in a higher pH buffering capacity (figure 5). 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, t/m^3).

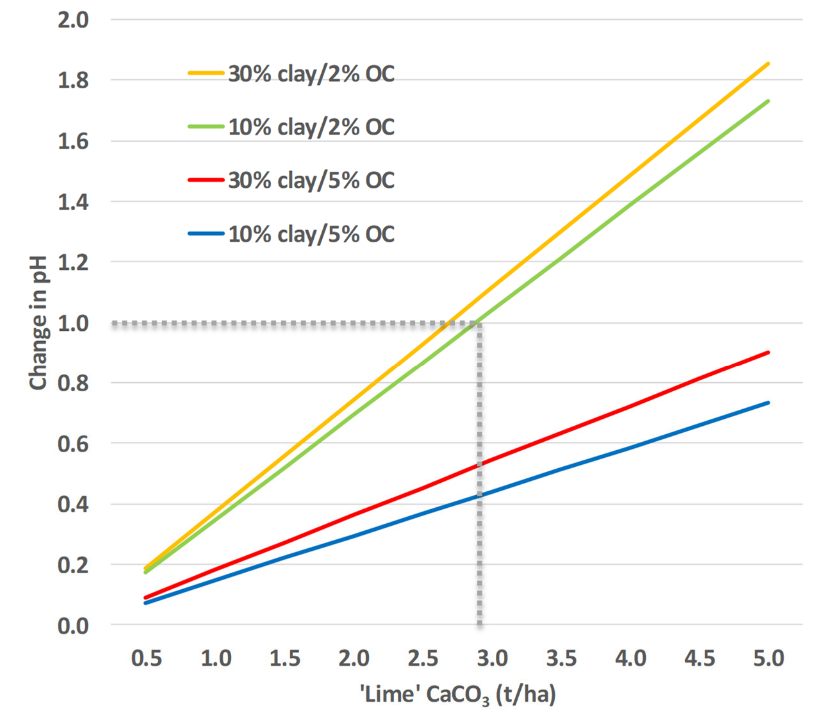

Fig 5. Relationships between the lime required to change pH (estimate of pH buffering capacity) and soil organic carbon and clay contents predicted by the pedotransfer function of Aitken *et al.* (1990).

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

$$\Delta pH = LR\ /\ pH\ BC \qquad (2)$$

Application of liming materials to surface soils without incorporation, to alleviate soil acidity takes 2-3 years to have full impact (Miller, 2017a). 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).

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

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).

Liming does not stop soil acidification. Rather soils re-acidify at the new soil pH level. 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 neutralize 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:

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

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 long-term field trials (Lisa Miller *pers. comm.*). The cropping system was assumed to be moderately acidifying with annual acid load of 110 kg/ha $CaCO_3$ equivalents, consistent with acidification rates observed in local long-term field trials (Miller 2018).

Crop yield responses

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 5 (below) 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).

$$Y_r = 1 - e^{(-\gamma * \max(0,\ pH - \delta))} \qquad (5)$$

Table 2. Coefficients (in equation 5) 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 6 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%.

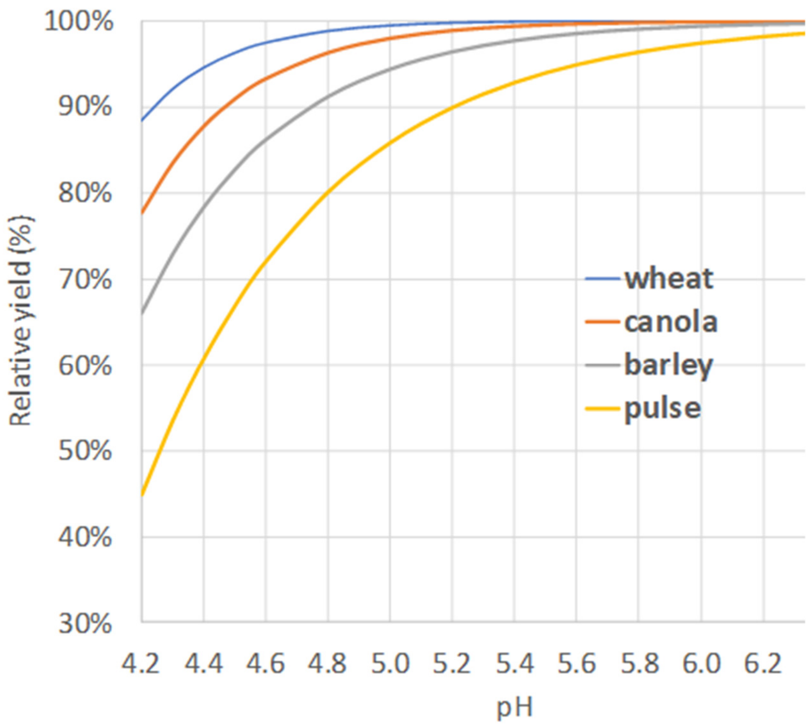

Fig 6. Relative yield by crop type predicted by the function from the Optlime tool (Gazey 2008) **calibrated to SFS trial results.**

Marginal gross margins for cropping activities

Absolute yields and gross crop returns were estimated by multiplying Y_r by the water-limited yield (Y_{max}) and the crop unit price (P) (table 3). Average values were used for cross-site comparisons; while distributions were used for uncertainty analysis.

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). A 15% allowance was applied for uncertainty analysis to reflect the experimental/modelled yield gap (i.e. the difference between the commercial yield achieved by farmers and the water-limited yield) (Nigussie et al. 2018).

The average and variance in crop prices were estimated from 5 years' data in the GRDC budget guide (GRDC 2018).

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

Variable	Category	Distribution	Wheat	Canola	Barley	Faba beans
Water limited yield (t/ha)	Deterministic for cross-site comparisons	5-year average	3.7	3.2	4.6	3.5
	Stochastic (for uncertainty analysis)	RiskUniform (min,max) max = 5-year average min = 15% discount	3.7-4.3	3.2-3.7	4.6-5.4	3.5-4.2
Price ($/t)	Deterministic for cross-site comparisons	5-year averages	270	512	265	442
	Stochastic (for uncertainty analysis)	RiskNormal (mean,var) 5-year averages truncated at 5% and 95% percentiles	270, 31	512, 30	265, 42	442, 115
Variable costs ($/t)						
• levies	Deterministic	2018 values	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
Marginal GM ($/t)	Deterministic	5-year average	222	462	217	392

Accounting for costs that vary with yield, the marginal GM for the acid tolerant rotation (BWCWW) was $270/t (on average), and the marginal GM for the acid sensitive rotation (BPCWW) was $300/t (on average).

Costs for the precision strategy

Costs for the precision strategy (table 4) were based on contract rates to avoid difficulties due to the scale of operations (Malcolm *et al.* 2005, p 104). Mapping costs were commercial rates of $14/ha adjusted for bundled testing costs (Precision Agriculture *pers. comm.*). VR spreading costs were $16/ha which included an additional $4/ha over uniform application ($12/ha) (Dellavedova Fertiliser Services, *pers. comm.*).

Testing costs for the intensive point sampling assumed 2 cores/ha costed at $18/sample (Nutrient Advantage, 2018). This was considerably more than for the traditional sampling method which requires only one composite sample (comprising 30 cores). Lime costs (delivered and spread) assumed a neutralizing 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).

Table 4. Costs for the precision strategy

Item	$/ha	$/ha @ 100% NV	$/t @ 90% NV	$/t @ 100% NV
Mapping and soil testing costs	**43**			
• pH mapping	7			
• Laboratory analysis of soil samples (2 top-soil samples /ha @ $18 each)	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**		

Total costs amounted to about $200/ha calculated at 100% NV and based on a lime rate of 2.5t/ha.

Residual/salvage value

The residual value (RV) of 'unused' lime stored in the soil at the end of the planning horizon was calculated as in equation 6:

$$RV = [(pH_{t=n} - pH_{t=0}) \times pH\ BC] / (1+r)^n \qquad (6)$$

RESULTS

Payoff from the profit-maximising precision strategy

The profit maximising precision strategy assumes the producer has a high level of 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. The average lime rate for each of the 10 case-study paddocks growing more acid tolerant crops (BWCWW) is shown in figure 7a (see also Appendix A).

Net benefits increased rapidly as the paddock-average pH_{Ca} declined and increased rapidly at pH levels below about 4.8. The annualised NPV ranged from $12/ha/yr at Mininera to $199/ha/yr at Seaspray (figure 7d). Liming of all 10 paddocks met the required nominal return on capital of 10% p.a (figure 7e).

Liming costs (figure 7b) had a material effect on the size of the annualised returns (figure 7d). However, productivity gains due to increased yield were much more influential in determining differences in the net benefits between case-study paddocks (figure 7c).

Financial feasibility was determined using the pay-back period. Reflecting the relative profitability, the payback period was generally about 5-6 years for pH levels above 4.8, but a much quicker 1 year for the highly acidic paddock at Seaspray (figure 7f).

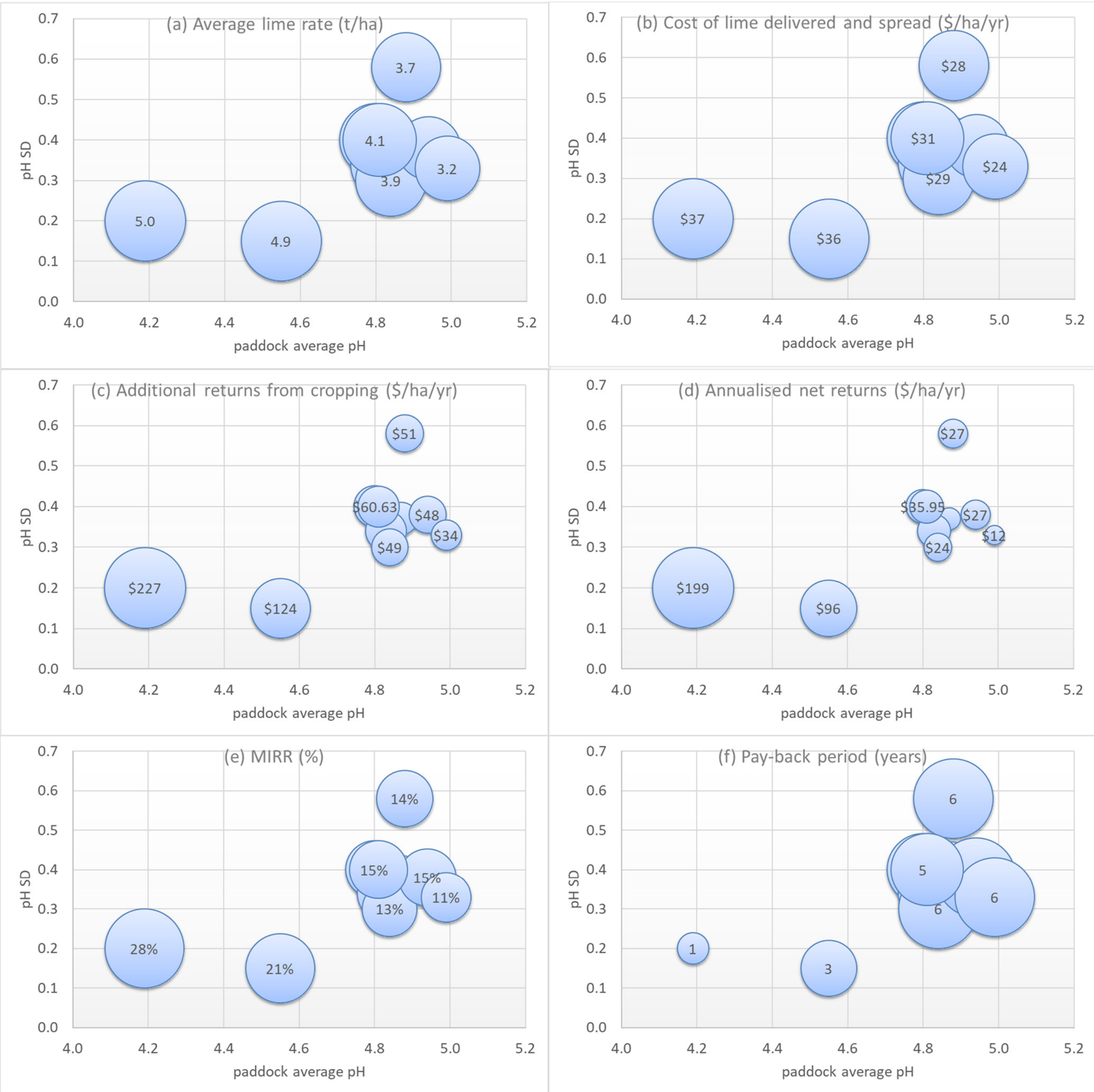

Fig 7. Change in the (a) average lime rate, (b) lime cost, (c) returns from cropping, (d) annualised net returns (e) MIRR and (f) pay-back period for each case-study paddock: profit-maximising VR liming strategy (liming scenario 1) and acid tolerant crop rotation.

These findings suggest that net benefits would be very sensitive to assumptions about crop types (acid tolerant v acid sensitive), and crop prices and yield potential over the planning horizon (risky variables in the analysis). Figure 8 shows that the net benefits of liming the paddock at Newlyn were substantially greater and more uncertain if the crop rotation included an acid-sensitive crop such as faba beans (BPCWW). More details about the net benefits of liming for each of the case-study paddocks with an acid sensitive crop rotation are contained in Appendices B to K.

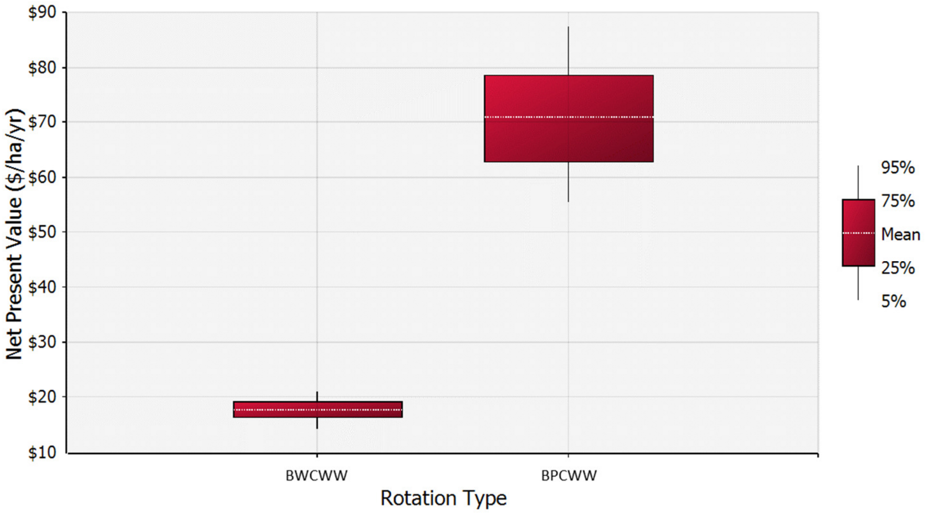

Fig 8. Range in annualised net benefits at Newlyn for VR application of lime (scenario 1) by rotation type.

Net benefits of alternative liming strategies

The robustness of the 'traditional' approach (scenario 4) when acid tolerant crops are grown is shown in table 5 and Appendices A-J. This low information, low cost strategy is generally superior in profit terms to all other liming strategies when acid tolerant crops are grown. For example, at Werneth, the annualised net benefits of the traditional approach were $31/ha compared to between $25 and $27/ha for the scenarios requiring intensive point sampling (scenarios 1, 2 and 3). The pay-back period was also typically 3-4 years, and at least 1-2 years sooner than for the liming strategies requiring a high level of information.

Table 5. Annualised net benefits of various liming strategies for each case-study paddock ($/ha/yr)

Liming strategy	**Traditional**	**Traditional**	**Precision**	**Uniform**	**Precision**	**Precision**
Acidity management scenario	**4**	**4**	**3**	**2**	**1**	**1**
Intensive point sampling?	**No**	**No**	**Yes**	**Yes**	**Yes**	**Yes**
Liming goal	**Target 5.5**	**Target 5.5**	**Target 5.5**	**Profit**	**Profit**	**Profit**
Application method	**Uniform**	**Uniform**	**VRA**	**Uniform**	**VRA**	**VRA**
Rotation type	**tolerant**	**sensitive**	**tolerant**	**tolerant**	**tolerant**	**sensitive**
Case-study paddock						
• Seaspray	$206.11	$331.79	$199.17	$199.83	$199.18	$324.86
• Winnindoo	$102.60	$194.59	$95.80	$97.03	$96.45	$195.45
• Miepoll	$42.41	$101.55	$34.91	$36.50	$35.95	$103.41
• Devenish	$21.40	$59.70	$15.68	$16.12	$16.10	$66.41
• Lilliput	$33.02	$82.73	$26.83	$27.65	$27.20	$88.03
• Werneth	$31.41	$74.71	$25.17	$27.01	$27.15	$84.95
• Mininera	$18.23	$55.02	$11.57	$12.56	$12.04	$59.91
• Gatum	$41.10	$98.54	$34.30	$35.27	$34.90	$100.73
• Maroona	$40.06	$94.71	$34.11	$34.51	$34.41	$97.43
• Newlyn	$29.67	$75.56	$24.10	$24.55	$24.48	$81.25

Importantly, when an acid sensitive crop is included in the rotation, the profit maximizing VR strategy is superior to the traditional approach; particularly if the paddock under consideration has a pH greater than about 4.5 and a CV greater than about 4%. For example, at Werneth, the annualised net benefits of the profit-maximising VR strategy (scenario 1) was $85/ha compared to $75/ha for the traditional approach (scenario 4).

Following intensive point sampling, the profit maximizing approach is generally superior to the target 5.5 approach. The exception being the very homogenous paddock at Seaspray. Furthermore, uniform application was generally more profitable to VR application. The one exception being the paddock at Werneth which had the highest in-paddock variation when measured using the interpolated pH data.

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 requiring a high level of data collection and management, interpretation, and judgement. The DCF model described in this study demonstrates the nature of the data, analysis and interpretation involved in the decision-making process.

When acid tolerant crops are grown, the net benefits of liming can be maximised using low-cost traditional practices. However, if the decision-maker wants the option of planting high-value, acid-sensitive crops then it would pay to pursue a profit-maximising strategy involving intensive point sampling. If the paddock under consideration has considerably high variability, greater than that observed in the case-study paddocks in this study, then VR application would be superior to uniform application.

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Appendix A: Data for bubble plots (figure 7)

Table A.1. Annualised benefits and costs on a per hectare basis for the VR liming strategy (scenario 1) for an acid tolerant crop rotation by case-study paddock

Case-study paddock	Seaspray	Winnindoo	Miepoll	Devenish	Lilliput	Werneth	Mininera	Gatum	Maroona	Newlyn
pH_{Ca} mean	4.19	4.55	4.8	4.87	4.88	4.94	4.99	4.81	4.83	4.84
• SD	0.2	0.15	0.4	0.37	0.58	0.38	0.33	0.4	0.34	0.3
• CV	4.8%	3.3%	8.3%	7.6%	11.9%	7.7%	6.6%	8.3%	7.0%	6.2%
Average lime rate (t/ha)	5.0	4.9	4.1	3.2	3.7	3.1	3.2	4.1	4.1	3.9
Benefits ($/ha/yr)										
• Additional returns (net)	$227	$124	$60.63	$38	$51	$48	$34	$60	$59	$49
• Residual value of lime	$15.63	$15.34	$12.18	$8.85	$10.71	$8.05	$8.68	$12.15	$12.40	$11.43
Costs ($/ha/yr)										
• Laboratory analysis of soil samples	-$5.28	-$5.28	-$5.28	-$5.28	-$5.28	-$5.28	-$5.28	-$5.28	-$5.28	-$5.28
• pH mapping	-$1.03	-$1.03	-$1.03	-$1.03	-$1.03	-$1.03	-$1.03	-$1.03	-$1.03	-$1.03
• Effective lime cost (delivered)	-$34.20	-$33.67	-$27.95	-$21.97	-$25.32	-$20.57	-$21.66	-$27.92	-$28.37	-$26.62
• VRA	-$2.61	-$2.61	-$2.60	-$2.61	-$2.61	-$2.53	-$2.59	-$2.61	-$2.61	-$2.60
Net benefits ($/ha/yr)	$199	$96	$35.95	$16	$27	$27	$12	$35	$34	$24
MIRR (%)	28%	21%	15%	12%	14%	15%	11%	15%	15%	13%
Pay-back period (years)	1	3	5	6	6	6	6	5	5	6

Figure B.1. VR Lime prescriptions for Seaspray

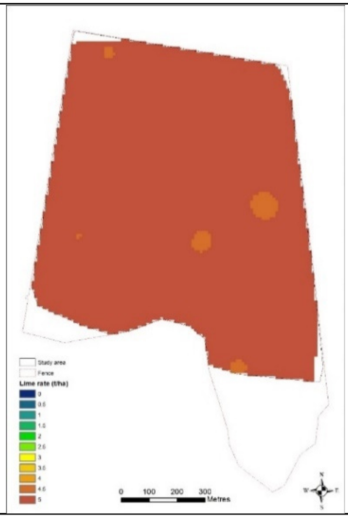
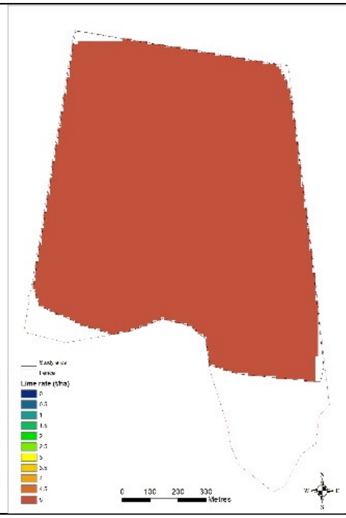
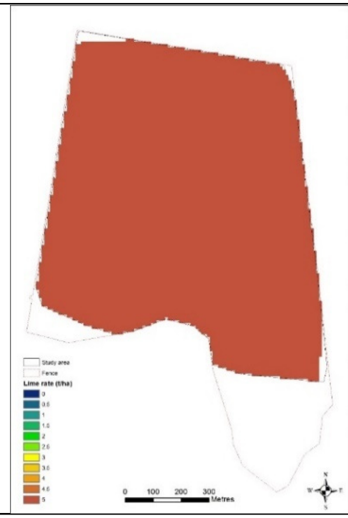
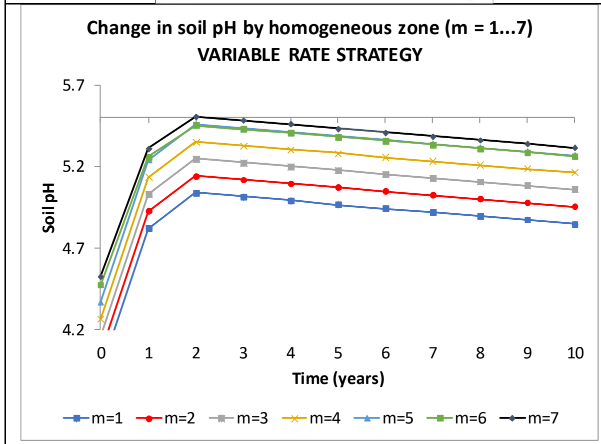
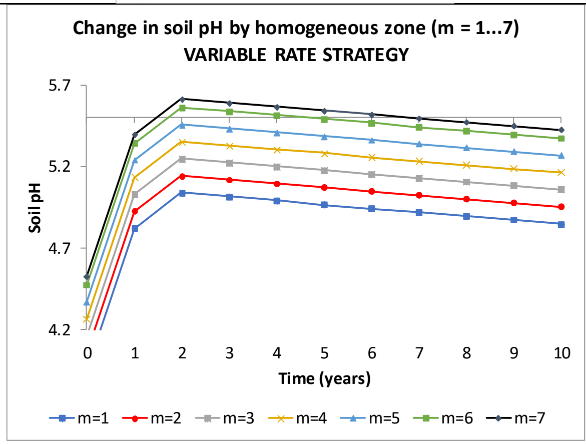
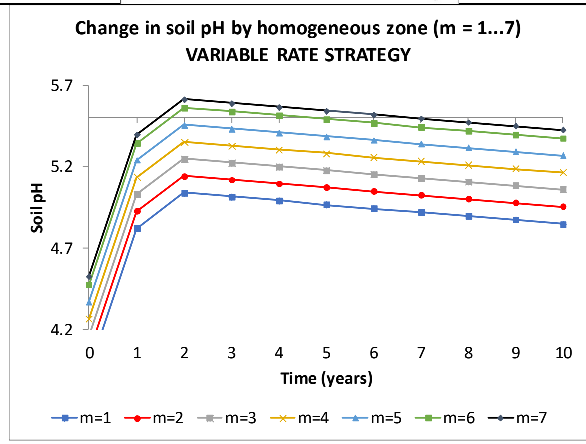
A. Target 5.5 liming rates for acid tolerant crop rotation (Scenario 3)	B. Profit maximising liming rates for acid tolerant crop rotation (Scenario 1)	C. Profit maximising liming rates for acid sensitive crop rotation (Scenario 1)
		
		

Table B.1 Lime prescription for the paddock at Seaspray (t/ha) @100% NV

	$pH_{Ca\ t=0}$ mid-point	Portion of paddock	Target 5.5 Uniform rate	Target 5.5 Uniform rate	Target 5.5 VRA	Profit maximizing Uniform rate	Profit maximizing VRA	Profit maximising VRA
Acidity management scenario			**4**	**4**	**3**	**2**	**1**	**1**
Information level			low	low	high	high	high	high
Rotation type			tolerant	sensitive	tolerant	tolerant	tolerant	sensitive
Homogeneous zone								
1	3.95	0.02	5.0	5.0	5.0	5.0	5.0	5.0
2	4.06	0.09	5.0	5.0	5.0	5.0	5.0	5.0
3	4.16	0.34	5.0	5.0	5.0	5.0	5.0	5.0
4	4.27	0.41	5.0	5.0	5.0	5.0	5.0	5.0
5	4.37	0.13	5.0	5.0	5.0	5.0	5.0	5.0
6	4.48	0.01	5.0	5.0	4.5	5.0	5.0	5.0
7	4.53	0.00	5.0	5.0	4.5	5.0	5.0	5.0
Paddock total/mean	4.22	1.00	5.0	5.0	5.0	5.0	5.0	5.0
Annuity ($/ha/yr)			$206.11	$331.79	$199.17	$199.83	$199.18	$324.86
MIRR (%)			30%	36%	28%	28%	28%	33%
Pay-back period (years)			1 year	1 year	1 year	1 year	1 year	1 year

Note: the maximum allowable rate is 5.0 t/ha to avoid problems of over-liming (such as trace element deficiencies).

Table B.2. Economic and financial analysis for VR liming at Seaspray: profit maximising, acid sensitive rotation

	Present value ($ over 10 years) 112 ha paddock	Equivalent annual net benefits for paddock ($/yr)	Equivalent annual net benefits per hectare ($/ha/yr)
Benefits			
• Additional returns on farm (net)	$269,239	$39,461	$352.33
• Residual value of lime	$11,945	$1,751	$15.63
Costs			
• Laboratory analysis of soil samples	-$4,032	-$591	-$5.28
• pH mapping	-$784	-$115	-$1.03
• Effective lime cost, delivered	-$26,133	-$3,830	-$34.20
• VRA	-$1,991	-$292	-$2.61
Net benefits in current dollars	$248,244	$36,384	$324.86
MIRR (%)	33%	33%	33%
Pay-back period (years)		1 year	

Appendix C: Winnindoo

Figure C.1. VR Lime prescriptions for Winnindoo

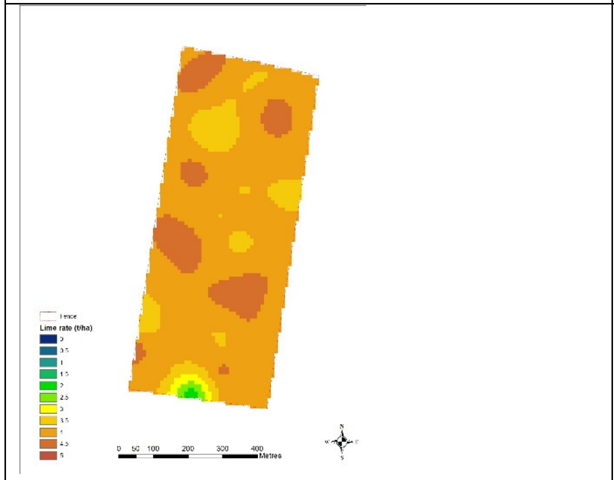
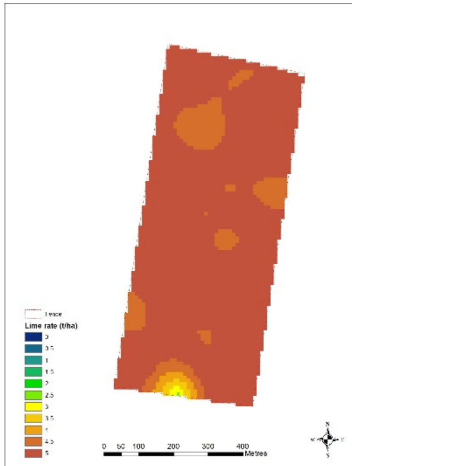
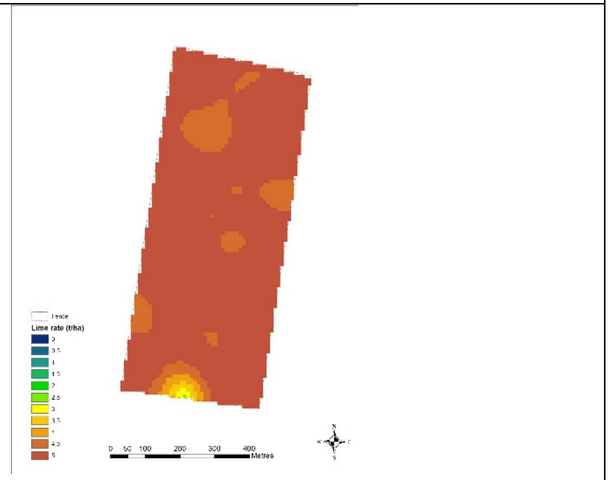
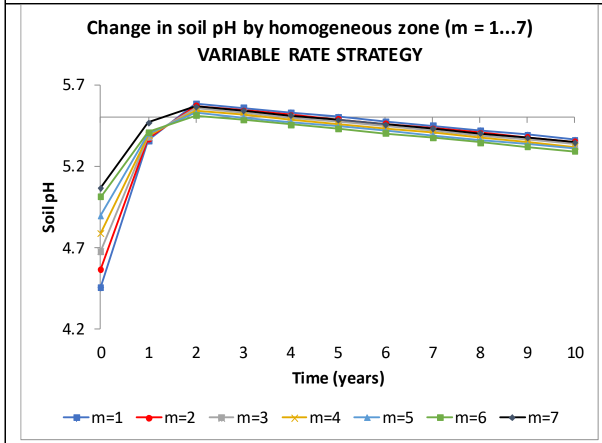
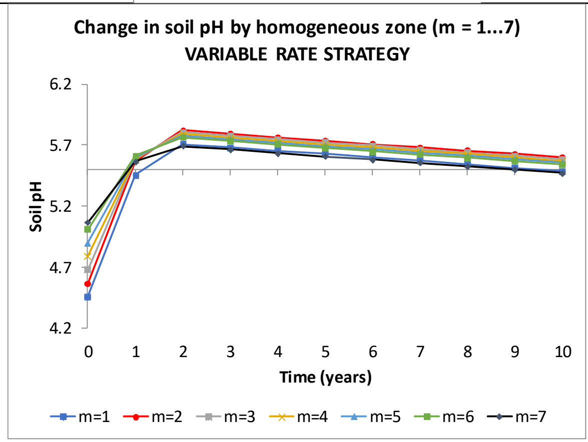
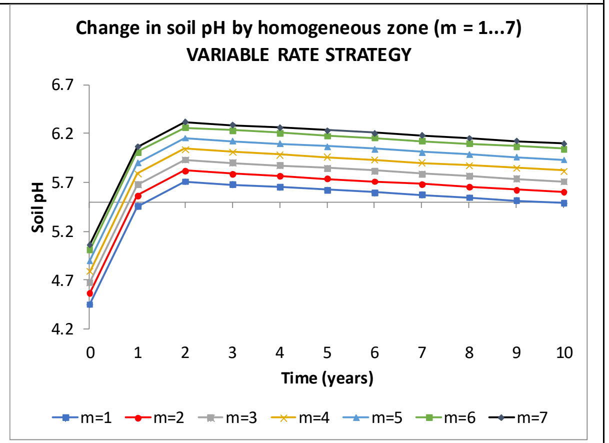
A. Target 5.5 liming rates for acid tolerant crop rotation (Scenario 3)	B. Profit maximising liming rates for acid tolerant crop rotation (Scenario 1)	C. Profit maximising liming rates for acid sensitive crop rotation (Scenario 1)
		
		

Table C.1 Lime prescription for the paddock at Winnindoo (t/ha) @100% NV

	$pH_{Ca\ t=0}$ mid-point	Portion of paddock	Target 5.5 Uniform rate	Target 5.5 Uniform rate	Target 5.5 VRA	Profit maximizing Uniform rate	Profit maximizing VRA	Profit maximising VRA
Acidity management scenario			**4**	**4**	**3**	**2**	**1**	**1**
Information level			low	low	high	high	high	high
Rotation type			tolerant	sensitive	tolerant	tolerant	tolerant	sensitive
Homogeneous zone								
1	4.46	0.13	4.0	4.0	4.5	5.0	5.0	5.0
2	4.57	0.75	4.0	4.0	4.0	5.0	5.0	5.0
3	4.68	0.11	4.0	4.0	3.5	5.0	4.5	5.0
4	4.79	0.01	4.0	4.0	3.0	5.0	4.0	5.0
5	4.90	0.01	4.0	4.0	2.5	5.0	3.5	5.0
6	5.01	0.00	4.0	4.0	2.0	5.0	3.0	5.0
7	5.07	0.00	4.0	4.0	2.0	5.0	2.5	5.0
Paddock total/mean	4.57	1.00	4.0	4.0	4.0	5.0	4.9	5.0
Annuity ($/ha/yr)			$102.60	$194.59	$95.80	$97.03	$96.45	$195.45
MIRR (%)			25%	32%	23%	21%	21%	28%
Pay-back period (years)			2 years	2 years	3 years	3 years	3 years	2 years

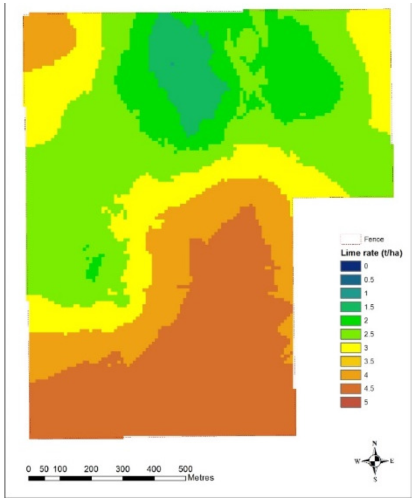
Note: the maximum allowable rate is 5.0 t/ha to avoid problems of over-liming (such as trace element deficiencies).

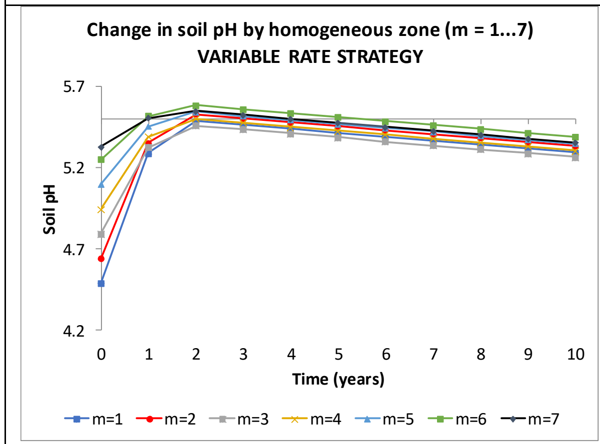
Table C.2. Economic and financial analysis for VR liming at Winnindoo: profit maximizing, acid sensitive rotation

	Present value ($ over 10 years) 40 ha paddock	Equivalent annual net benefits for paddock ($/yr)	Equivalent annual net benefits per hectare ($/ha/yr)
Benefits			
• Additional returns on farm (net)	$60,841	$8,917	$222.93
• Residual value of lime	$4,266	$625	$15.63
Costs			
• Laboratory analysis of soil samples	-$1,440	-$211	-$5.28
• pH mapping	-$280	-$41	-$1.03
• Effective lime cost, delivered	-$9,333	-$1,368	-$34.20
• VRA	-$711	-$104	-$2.61
Net benefits in current dollars	$53,342	$7,818	$195.45
MIRR (%)	28%	28%	28%
Pay-back period (years)		2 years	

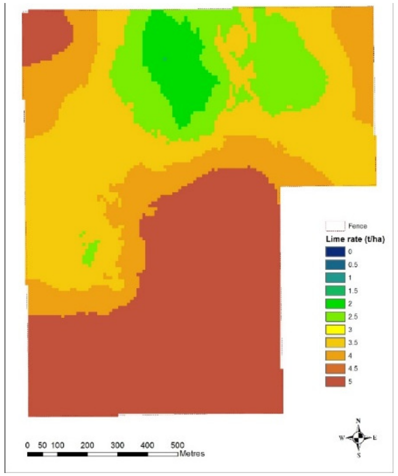
Figure D.1. VR Lime prescriptions for Miepoll

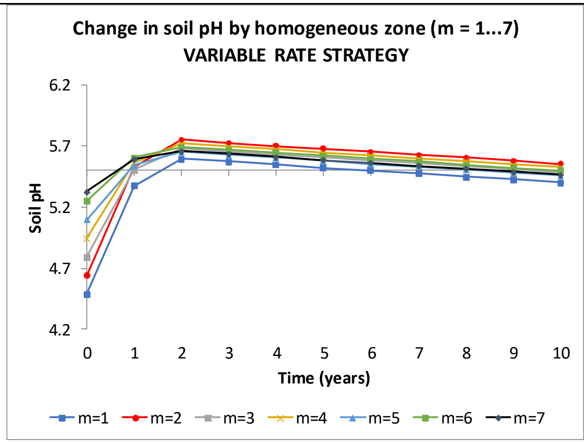
A. Target 5.5 liming rates for acid tolerant crop rotation (Scenario 3)



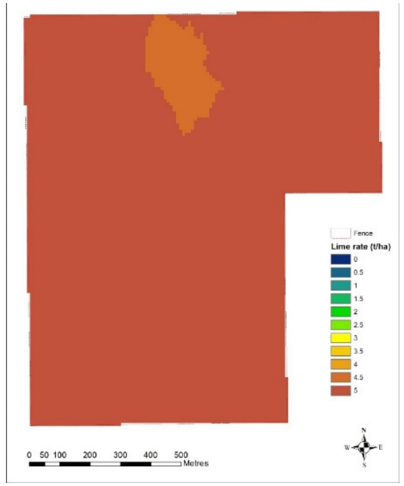


B. Profit maximising liming rates for acid tolerant crop rotation (Scenario 1)





C. Profit maximising liming rates for acid sensitive crop rotation (Scenario 1)



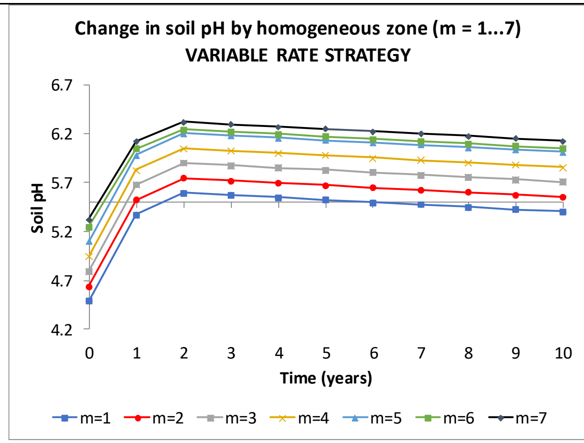


Table D.1 Lime prescription for the paddock at Miepoll (t/ha) @100% NV

	$pH_{Ca\ t=0}$ mid-point	Portion of paddock	Target 5.5 Uniform rate	Target 5.5 Uniform rate	Target 5.5 VRA	Profit maximizing Uniform rate	Profit maximizing VRA	Profit maximising VRA
Acidity management scenario			**4**	**4**	**3**	**2**	**1**	**1**
Information level			low	low	high	high	high	high
Rotation type			tolerant	sensitive	tolerant	tolerant	tolerant	sensitive
Homogeneous zone								
1	4.49	0.01	3.5	3.5	4.5	4.0	5.0	5.0
2	4.64	0.12	3.5	3.5	4.0	4.0	5.0	5.0
3	4.79	0.84	3.5	3.5	3.0	4.0	4.0	5.0
4	4.95	0.03	3.5	3.5	2.5	4.0	3.0	5.0
5	5.10	0.01	3.5	3.5	2.0	4.0	2.5	5.0
6	5.25	0.00	3.5	3.5	1.5	4.0	1.5	4.5
7	5.33	0.00	3.5	3.5	1.0	4.0	1.0	4.0
Paddock total/mean	4.77	1.00	3.5	3.5	3.1	4.0	4.1	5.0
Annuity ($/ha/yr)			$42.41	$101.55	$34.91	$36.50	$35.95	$103.41
MIRR (%)			19%	26%	16%	16%	15%	22%
Pay-back period (years)			3 years	2 years	4 years	5 years	5 years	2 years

Note: the maximum allowable rate is 5.0 t/ha to avoid problems of over-liming (such as trace element deficiencies).

Table D.2. Economic and financial analysis for VR liming at Miepoll: profit maximizing, acid sensitive rotation

	Present value ($ over 10 years) 134 ha paddock	Equivalent annual net benefits for paddock ($/yr)	Equivalent annual net benefits per hectare ($/ha/yr)
Benefits			
• Additional returns on farm (net)	$119,622	$17,533	$130.84
• Residual value of lime	$14,262	$2,090	$15.60
Costs			
• Laboratory analysis of soil samples	-$4,824	-$707	-$5.28
• pH mapping	-$938	-$137	-$1.03
• Effective lime cost, delivered	-$31,202	-$4,573	-$34.13
• VRA	-$2,378	-$348	-$2.60
Net benefits in current dollars	$94,543	$13,857	$103.41
MIRR (%)	22%	22%	22%
Pay-back period (years)		2 years	

.

Appendix E: Devenish

Figure E.1. VR Lime prescriptions for Devenish

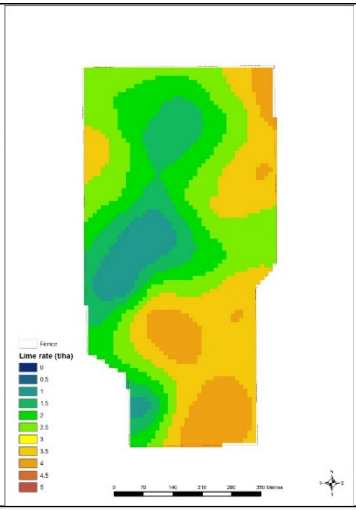
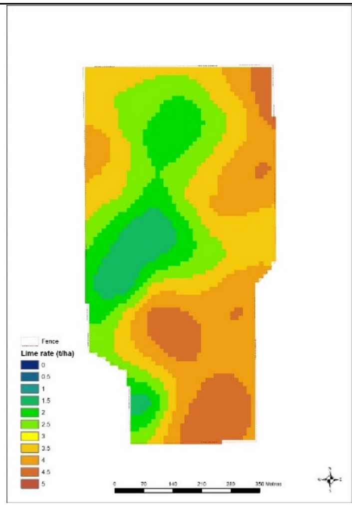
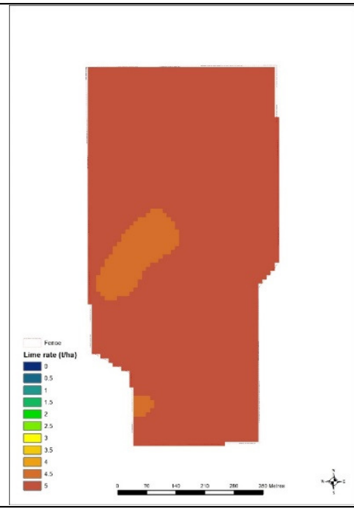
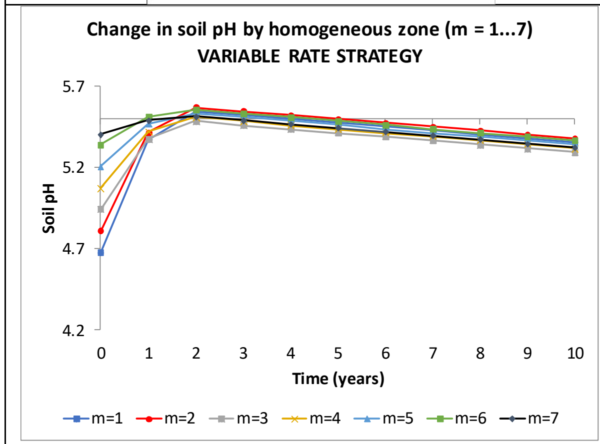
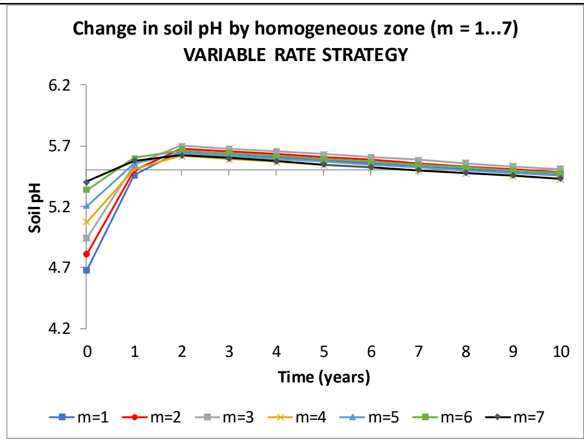
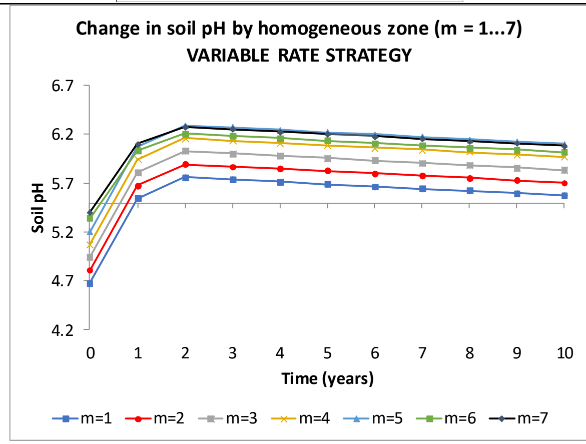
A. Target 5.5 liming rates for acid tolerant crop rotation (Scenario 3)	B. Profit maximising liming rates for acid tolerant crop rotation (Scenario 1)	C. Profit maximising liming rates for acid sensitive crop rotation (Scenario 1)
		
		

Table E.1 Lime prescription for the paddock at Devenish (t/ha) @100% NV

	$pH_{Ca\ t=0}$ mid-point	Portion of paddock	Target 5.5 Uniform rate	Target 5.5 Uniform rate	Target 5.5 VRA	Profit maximizing Uniform rate	Profit maximizing VRA	Profit maximising VRA
Acidity management scenario			**4**	**4**	**3**	**2**	**1**	**1**
Information level			low	low	high	high	high	high
Rotation type			tolerant	sensitive	tolerant	tolerant	tolerant	sensitive
Homogeneous zone								
1	4.68	0.12	2.5	2.5	4.0	3.5	4.5	5.0
2	4.81	0.25	2.5	2.5	3.5	3.5	4.0	5.0
3	4.94	0.24	2.5	2.5	2.5	3.5	3.5	5.0
4	5.07	0.19	2.5	2.5	2.0	3.5	2.5	5.0
5	5.21	0.13	2.5	2.5	1.5	3.5	2.0	5.0
6	5.34	0.07	2.5	2.5	1.0	3.5	1.5	4.0
7	5.40	0.00	2.5	2.5	0.5	3.5	1.0	4.0
Paddock total/mean	4.97	1.00	2.5	2.5	2.6	3.5	3.2	4.9
Annuity ($/ha/yr)			$21.40	$59.70	$15.68	$16.12	$16.10	$66.41
MIRR (%)			16%	24%	13%	12%	12%	18%
Pay-back (years)			5 years	2 years	6 years	6 years	6 years	2 years

Note: the maximum allowable rate is 5.0 t/ha to avoid problems of over-liming (such as trace element deficiencies).

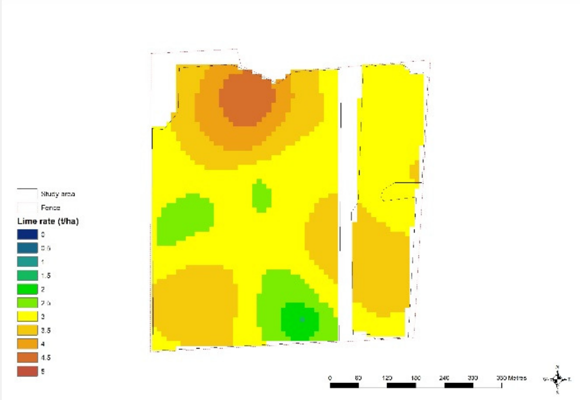
Table E.2. Economic and financial analysis for VR liming at Devenish: profit maximising, acid sensitive rotation

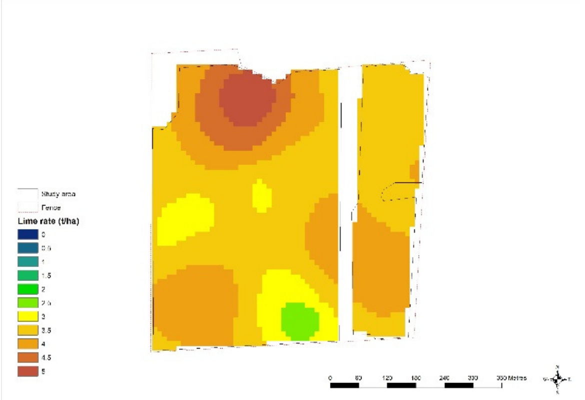
	Present value ($ over 10 years) 37 ha paddock	Equivalent annual net benefits for paddock ($/yr)	Equivalent annual net benefits per hectare ($/ha/yr)
Benefits			
• Additional returns on farm (net)	$23,649	$3,466	$93.68
• Residual value of lime	$3,882	$569	$15.38
Costs			
• Laboratory analysis of soil samples	-$1,332	-$195	-$5.28
• pH mapping	-$259	-$38	-$1.03
• Effective lime cost, delivered	-$8,517	-$1,248	-$33.74
• VRA	-$658	-$96	-$2.61
Net benefits in current dollars	$16,765	$2,457	$66.41
MIRR (%)	18%	18%	18%
Pay-back period (years)		2 years	

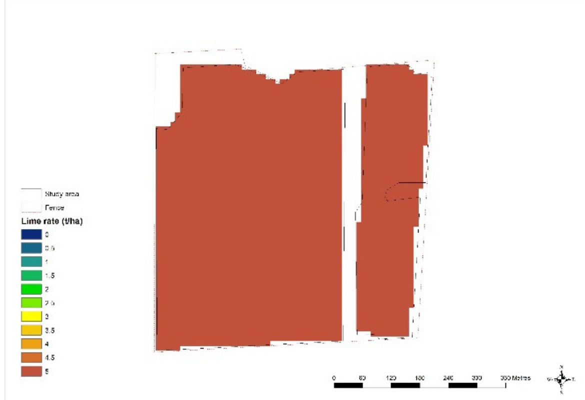
Appendix F: Lilliput

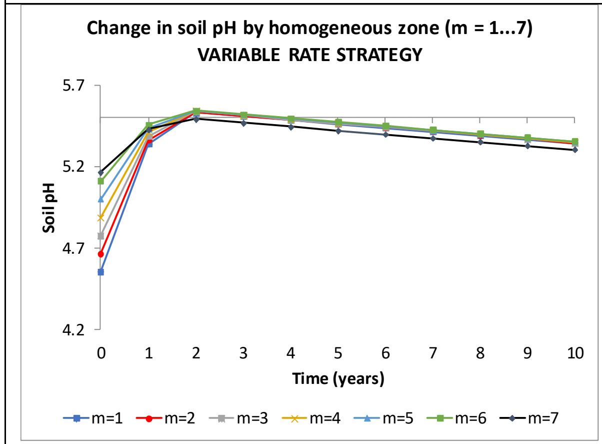
Figure F.1. VR Lime prescriptions for Lilliput

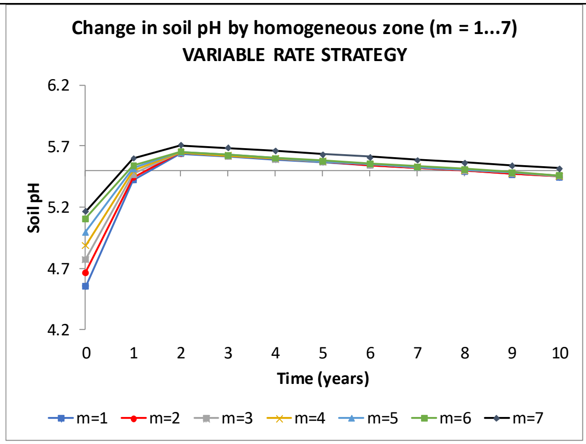
A. Target 5.5 liming rates for acid tolerant crop rotation (Scenario 3)	B. Profit maximising liming rates for acid tolerant crop rotation (Scenario 1)	C. Profit maximising liming rates for acid sensitive crop rotation (Scenario 1)











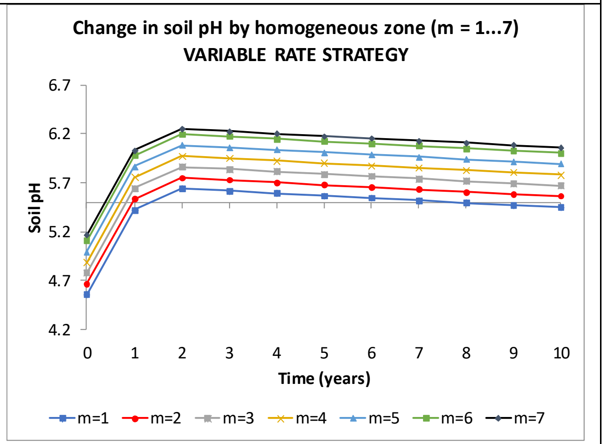


Table F.1 Lime prescription for the paddock at Lilliput (t/ha) @100% NV

	$pH_{Ca\ t=0}$ mid-point	Portion of paddock	Target 5.5 Uniform rate	Target 5.5 Uniform rate	Target 5.5 VRA	Profit maximizing Uniform rate	Profit maximizing VRA	Profit maximising VRA
Acidity management scenario			**4**	**4**	**3**	**2**	**1**	**1**
Information level			low	low	high	high	high	high
Rotation type			tolerant	sensitive	tolerant	tolerant	tolerant	sensitive
Homogeneous zone								
1	4.56	0.04	3.0	3.0	4.5	4.0	5.0	5.0
2	4.67	0.06	3.0	3.0	4.0	4.0	4.5	5.0
3	4.78	0.30	3.0	3.0	3.5	4.0	4.0	5.0
4	4.89	0.49	3.0	3.0	3.0	4.0	3.5	5.0
5	5.00	0.09	3.0	3.0	2.5	4.0	3.0	5.0
6	5.11	0.02	3.0	3.0	2.0	4.0	2.5	5.0
7	5.17	0.00	3.0	3.0	1.5	4.0	2.5	5.0
Paddock total/mean	4.84	1.00	3.0	3.0	3.2	4.0	3.7	5.0
Annuity ($/ha/yr)			$33.02	$82.73	$26.83	$27.65	$27.20	$88.03
MIRR (%)			18%	26%	15%	14%	14%	20%
Pay-back period (years)			3 years	2 years	6 years	4 years	6 years	2 years

Note: the maximum allowable rate is 5.0 t/ha to avoid problems of over-liming (such as trace element deficiencies).

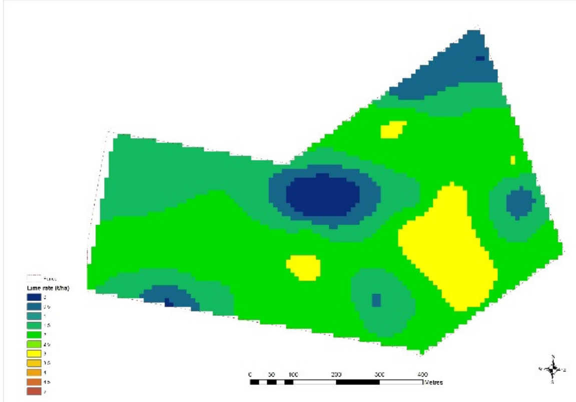
Table F.2. Economic and financial analysis for VR liming at Lilliput: profit maximising, acid tolerant rotation

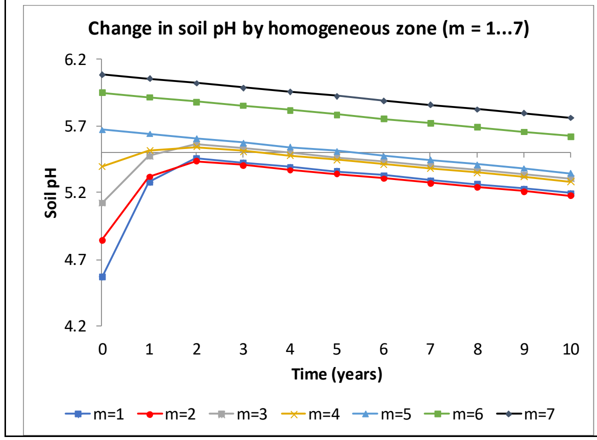
	Present value ($ over 10 years) 28 ha paddock	Equivalent annual net benefits for paddock ($/yr)	Equivalent annual net benefits per hectare ($/ha/yr)
Benefits			
• Additional returns on farm (net)	$22,066	$3,234	$115.50
• Residual value of lime	$2,986	$438	$15.63
Costs			
• Laboratory analysis of soil samples	-$1,008	-$148	-$5.28
• pH mapping	-$196	-$29	-$1.03
• Effective lime cost, delivered	-$6,533	-$958	-$34.20
• VRA	-$498	-$73	-$2.61
Net benefits in current dollars	$16,817	$2,465	$88.03
MIRR (%)	20%	20%	20%
Pay-back period (years)		2 years	

Appendix G: Werneth

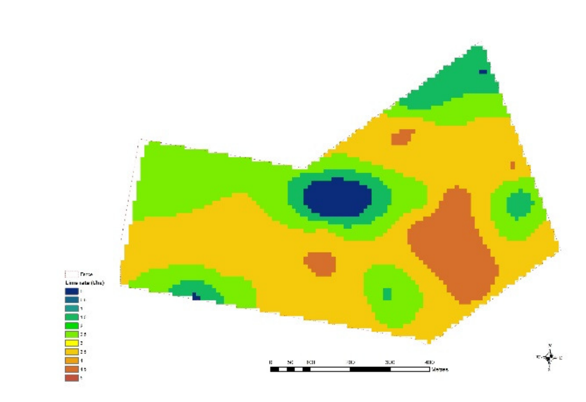
Figure G.1. VR Lime prescriptions for Werneth

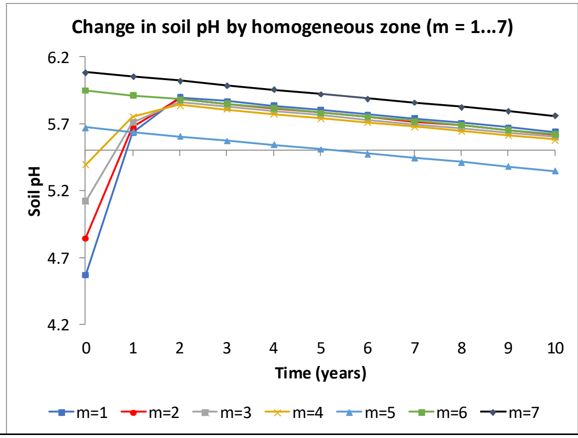
A. Target 5.5 liming rates for acid tolerant crop rotation (Scenario 3)



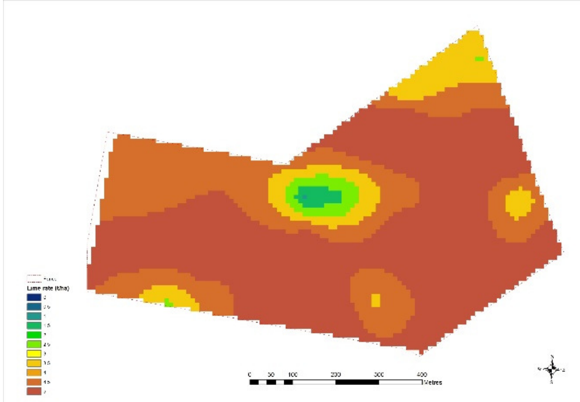


B. Profit maximising liming rates for acid tolerant crop rotation (Scenario 1)





C. Profit maximising liming rates for acid sensitive crop rotation (Scenario 1)



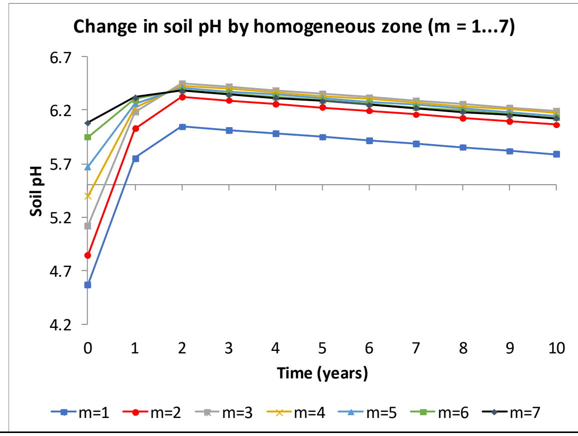


Table G.1 Lime prescriptions for the paddock at Werneth (t/ha) @100% NV

	$pH_{Ca\ t=0}$ mid-point	Portion of paddock	Target 5.5 Uniform rate	Target 5.5 Uniform rate	Target 5.5 VRA	Profit maximizing Uniform rate	Profit maximizing VRA	Profit maximising VRA
Acidity management scenario			**4**	**4**	**3**	**2**	**1**	**1**
Information level			**low**	**low**	**high**	**high**	**high**	**high**
Rotation type			**tolerant**	**sensitive**	**tolerant**	**tolerant**	**tolerant**	**sensitive**
Homogeneous zone								
1	4.57	0.09	2.0	2.0	3.0	3.0	4.5	5.0
2	4.85	0.49	2.0	2.0	2.0	3.0	3.5	5.0
3	5.12	0.30	2.0	2.0	1.5	3.0	2.5	4.5
4	5.40	0.09	2.0	2.0	0.5	3.0	1.5	3.5
5	5.67	0.02	2.0	2.0	0.0	3.0	0.0	2.5
6	5.95	0.01	2.0	2.0	0.0	3.0	0.0	1.5
7	6.08	0.00	2.0	2.0	0.0	3.0	0.0	1.0
Paddock total/mean	4.98	1.00	2.0	2.0	1.8	3.0	3.1	4.6
Annuity ($/ha/yr)			$31.41	$74.71	$25.17	$27.01	$27.15	$84.95
MIRR (%)			20%	28%	17%	15%	15%	21%
Pay-back (years)			3 years	2 years	4 years	6 years	6 years	2 years

Note: the maximum allowable rate is 5.0 t/ha to avoid problems of over-liming (such as trace element deficiencies).

Table G.2. Economic and financial analysis for VR liming at Werneth: profit maximising, acid sensitive rotation

	Present value ($ over 10 years) 49 ha paddock	Equivalent annual net benefits for paddock ($/yr)	Equivalent annual net benefits per hectare ($/ha/yr)
Benefits			
• Additional returns on farm (net)	$37,208	$5,453	$111.29
• Residual value of lime	$4,756	$697	$14.23
Costs			
• Laboratory analysis of soil samples	-$1,764	-$259	-$5.28
• pH mapping	-$343	-$50	-$1.03
• Effective lime cost, delivered	-$10,585	-$1,551	-$31.66
• VRA	-$871	-$127.68	-$2.61
Net benefits in current dollars	$28,401	$4,163	$84.95
MIRR (%)	21%	21%	21%
Pay-back period (years)		2 years	

Appendix H: Mininera

Figure H.1. VR Lime prescriptions for Mininera

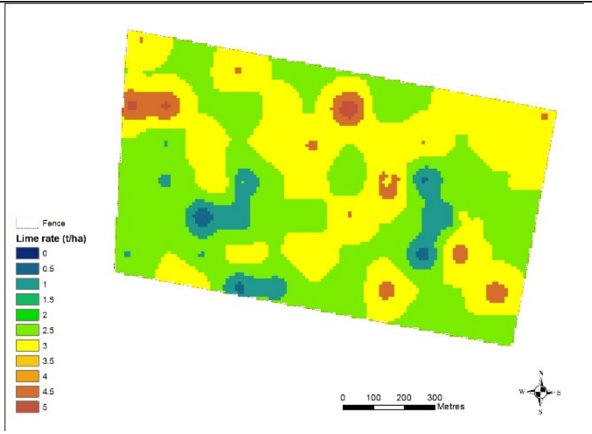
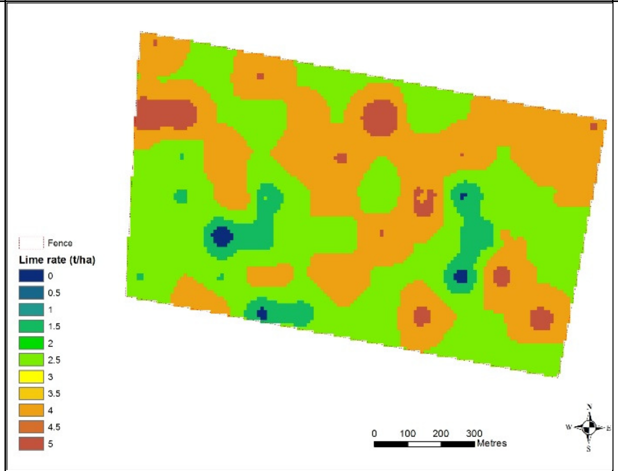
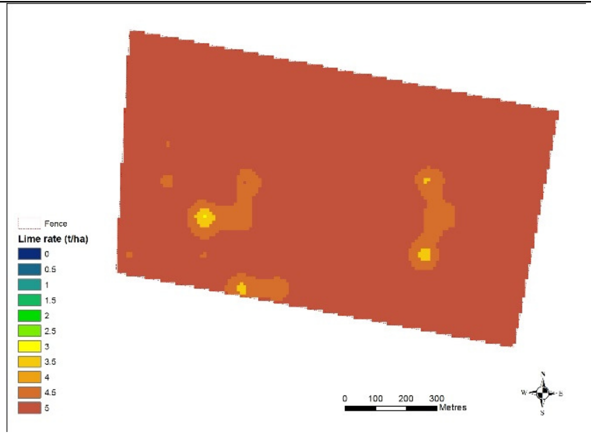
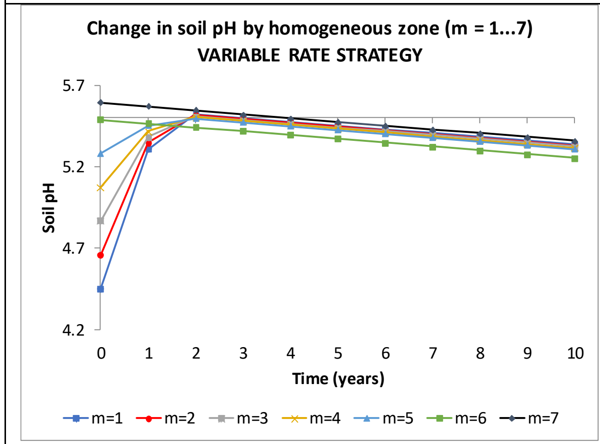
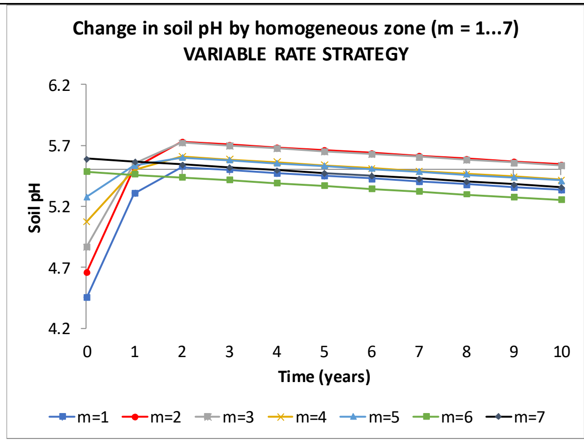
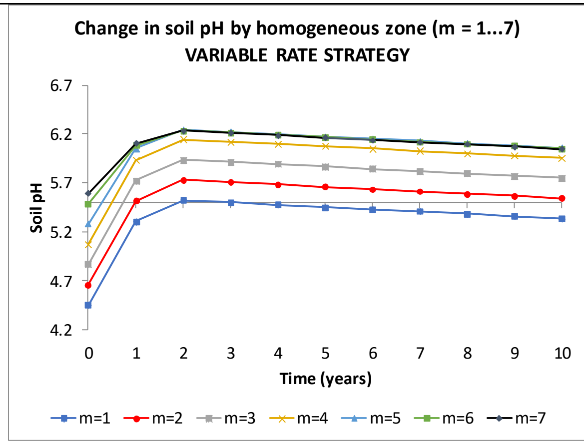
A. Target 5.5 liming rates for acid tolerant crop rotation (Scenario 3)	B. Profit maximising liming rates for acid tolerant crop rotation (Scenario 1)	C. Profit maximising liming rates for acid sensitive crop rotation (Scenario 1)
		
		

Table H.1 Lime prescription for the paddock at Mininera (t/ha) @100% NV

	$pH_{Ca\ t=0}$ mid-point	Portion of paddock	Target 5.5 Uniform rate	Target 5.5 Uniform rate	Target 5.5 VRA	Profit maximizing Uniform rate	Profit maximizing VRA	Profit maximising VRA
Acidity management scenario			**4**	**4**	**3**	**2**	**1**	**1**
Information level			low	low	high	high	high	high
Rotation type			tolerant	sensitive	tolerant	tolerant	tolerant	sensitive
Homogeneous zone								
1	4.45	0.00	2.5	2.5	5.0	3.5	5.0	5.0
2	4.66	0.03	2.5	2.5	4.0	3.5	5.0	5.0
3	4.87	0.43	2.5	2.5	3.0	3.5	4.0	5.0
4	5.07	0.47	2.5	2.5	2.0	3.5	2.5	5.0
5	5.28	0.06	2.5	2.5	1.0	3.5	1.5	4.5
6	5.49	0.01	2.5	2.5	0.0	3.5	0.0	3.5
7	5.59	0.00	2.5	2.5	0.0	3.5	0.0	3.0
Paddock total/mean	4.98	1.00	2.5	2.5	2.5	3.5	3.2	5.0
Annuity ($/ha/yr)			$18.23	$55.02	$11.57	$12.56	$12.04	$59.91
MIRR (%)			15%	23%	12%	11%	11%	17%
Pay-back (years)			5 years	2 years	6 years	6 years	6 years	2 years

Note: the maximum allowable rate is 5.0 t/ha to avoid problems of over-liming (such as trace element deficiencies).

Table H.2. Economic and financial analysis for VR liming at Mininera: profit maximising, acid sensitive rotation

	Present value ($ over 10 years) 108 ha paddock	Equivalent annual net benefits for paddock ($/yr)	Equivalent annual net benefits per hectare ($/ha/yr)
Benefits			
• Additional returns on farm (net)	$64,309	$9,426	$87.27
• Residual value of lime	$11,414	$1,673	$15.49
Costs			
• Laboratory analysis of soil samples	-$3,888	-$570	-$5.28
• pH mapping	-$756	-$111	-$1.03
• Effective lime cost, delivered	-$25,010	-$3,666	-$33.94
• VRA	-$1,920	-$281	-$2.61
Net benefits in current dollars	$44,149	$6,471	$59.91
MIRR (%)	17%	17%	17%
Pay-back period (years)		2 years	

Appendix I: Gatum

Figure I.1. VR Lime prescriptions for Gatum

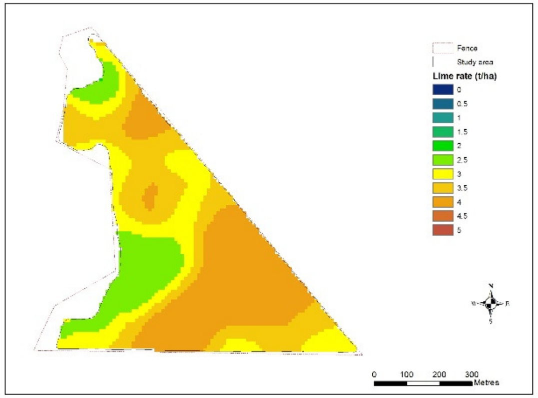
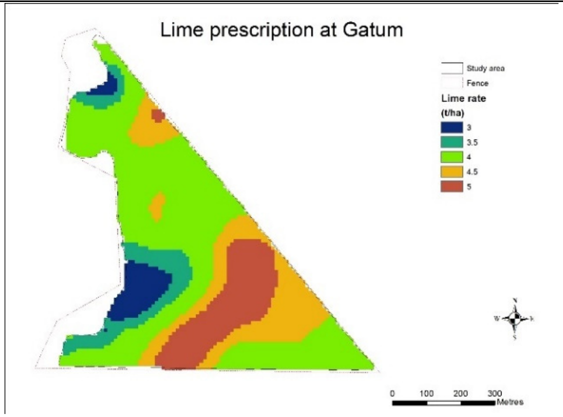
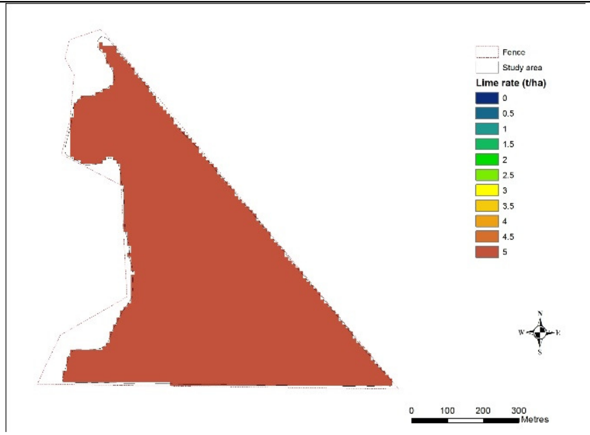
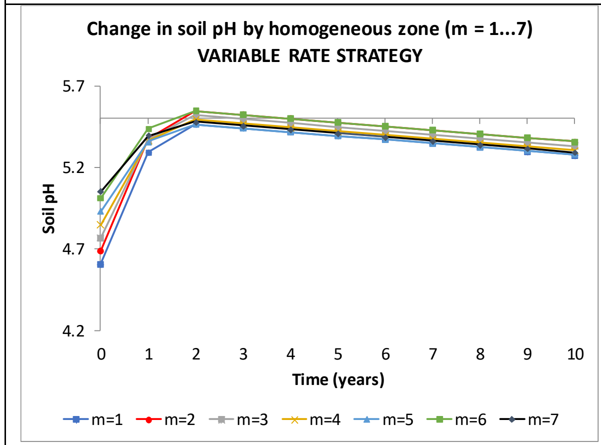
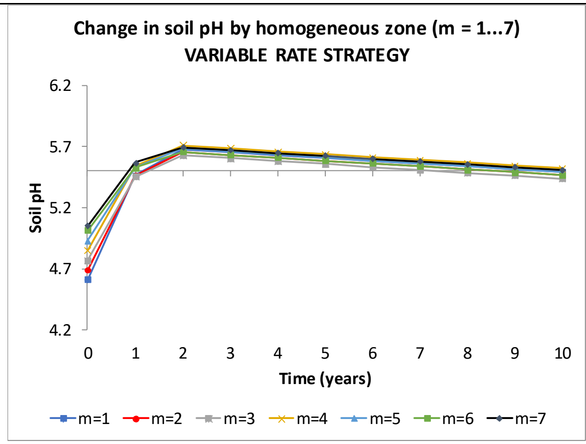
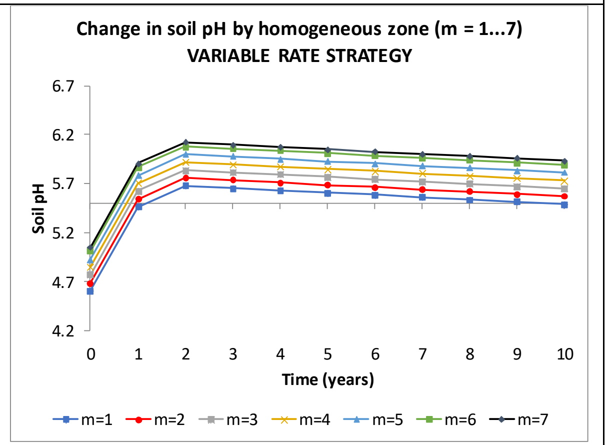
A. Target 5.5 liming rates for acid tolerant crop rotation (Scenario 3)	B. Profit maximising liming rates for acid tolerant crop rotation (Scenario 1)	C. Profit maximising liming rates for acid sensitive crop rotation (Scenario 1)
		
		

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Table I.1 Lime prescription for the paddock at Gatum (t/ha) @100% NV

	$pH_{Ca\ t=0}$ mid-point	Portion of paddock	Target 5.5 Uniform rate	Target 5.5 Uniform rate	Target 5.5 VRA	Profit maximizing Uniform rate	Profit maximizing VRA	Profit maximising VRA
Acidity management scenario			**4**	**4**	**3**	**2**	**1**	**1**
Information level			low	low	high	high	high	high
Rotation type			tolerant	sensitive	tolerant	tolerant	tolerant	sensitive
Homogeneous zone								
1	4.61	0.11	3.5	3.5	4.0	4.0	5.0	5.0
2	4.69	0.16	3.5	3.5	4.0	4.0	4.5	5.0
3	4.77	0.28	3.5	3.5	3.5	4.0	4.0	5.0
4	4.85	0.30	3.5	3.5	3.0	4.0	4.0	5.0
5	4.93	0.11	3.5	3.5	2.5	4.0	3.5	5.0
6	5.01	0.05	3.5	3.5	2.5	4.0	3.0	5.0
7	5.05	0.00	3.5	3.5	2.0	4.0	3.0	5.0
Paddock total/mean	4.79	1.00	3.5	3.5	3.3	4.0	4.1	5.0
Annuity ($/ha/yr)			$41.10	$98.54	$34.30	$35.27	$34.90	$100.73
MIRR (%)			18%	26%	16%	15%	15%	21%
Pay-back period (years)			3 years	2 years	5 years	5 years	5 years	2 years

Note: the maximum allowable rate is 5.0 t/ha to avoid problems of over-liming (such as trace element deficiencies).

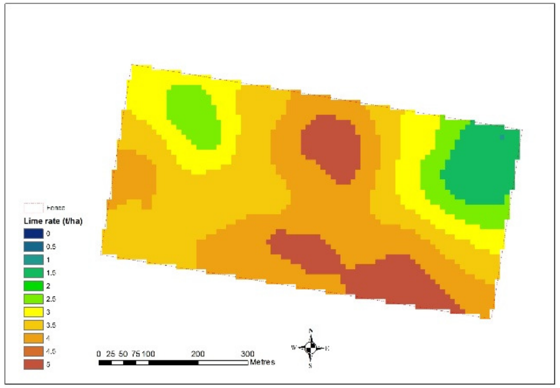
Table I.2. Economic and financial analysis for VR liming at Gatum: profit maximizing, acid sensitive rotation

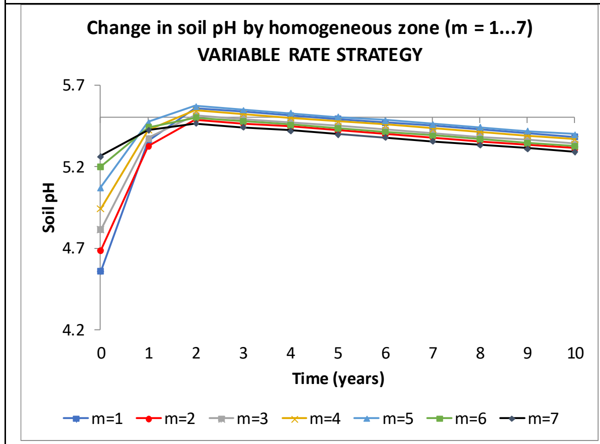
	Present value ($ over 10 years) 45 ha paddock	Equivalent annual net benefits for paddock ($/yr)	Equivalent annual net benefits per hectare ($/ha/yr)
Benefits			
• Additional returns on farm (net)	$39,363	$5,769	$128.21
• Residual value of lime	$4,800	$703	$15.63
Costs			
• Laboratory analysis of soil samples	-$1,620	-$237	-$5.28
• pH mapping	-$315	-$46	-$1.03
• Effective lime cost, delivered	-$10,500	-$1,539	-$34.20
• VRA	-$800	-$117	-$2.61
Net benefits in current dollars	$30,927	$4,533	$100.73
MIRR (%)	21%	21%	21%
Pay-back period (years)		2 years	

Appendix J: Maroona

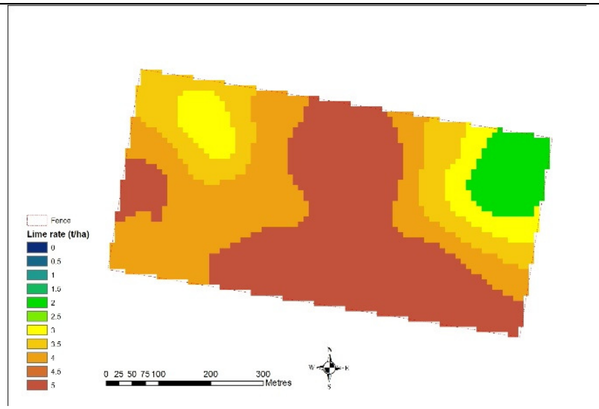
Figure J.1. VR Lime prescriptions for Maroona

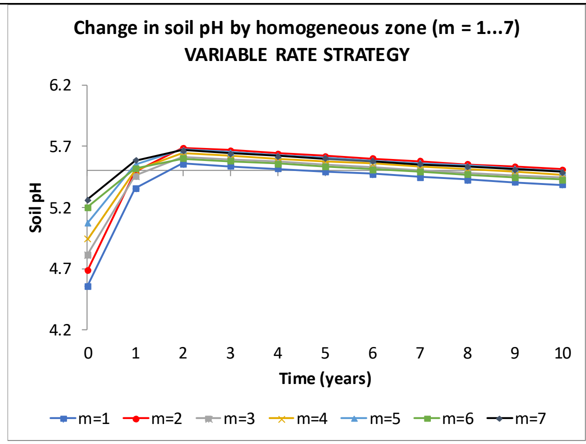
A. Target 5.5 liming rates for acid tolerant crop rotation (Scenario 3)



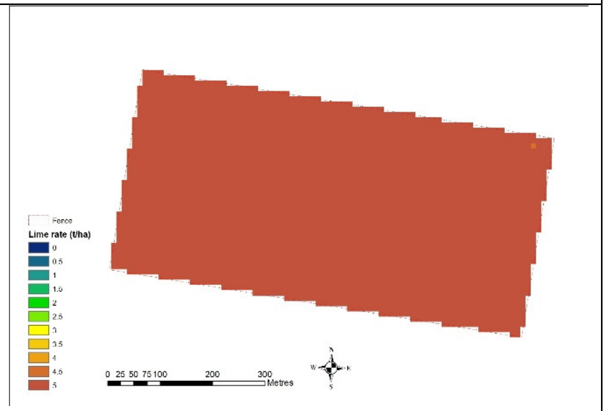


B. Profit maximising liming rates for acid tolerant crop rotation (Scenario 1)





C. Profit maximising liming rates for acid sensitive crop rotation (Scenario 1)



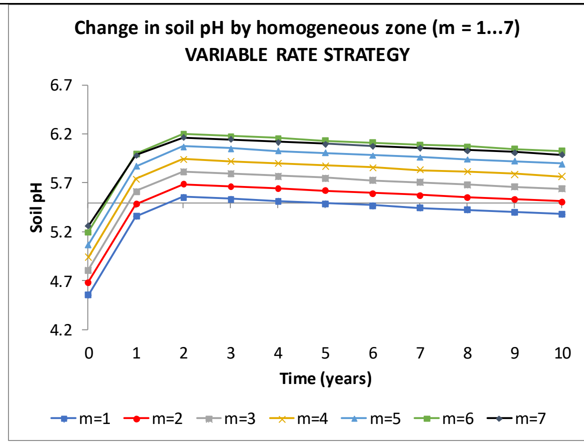


Table J.1 Lime prescription for the paddock at Maroona (t/ha) @100% NV

	$pH_{Ca\ t=0}$ mid-point	Portion of paddock	Target 5.5 Uniform rate	Target 5.5 Uniform rate	Target 5.5 VRA	Profit maximizing Uniform rate	Profit maximizing VRA	Profit maximising VRA
Acidity management scenario			**4**	**4**	**3**	**2**	**1**	**1**
Information level			low	low	high	high	high	high
Rotation type			tolerant	sensitive	tolerant	tolerant	tolerant	sensitive
Homogeneous zone								
1	4.56	0.12	3.5	3.5	5.0	4.5	5.0	5.0
2	4.69	0.30	3.5	3.5	4.0	4.5	5.0	5.0
3	4.81	0.28	3.5	3.5	3.5	4.5	4.0	5.0
4	4.94	0.15	3.5	3.5	3.0	4.5	3.5	5.0
5	5.07	0.08	3.5	3.5	2.5	4.5	3.0	5.0
6	5.20	0.06	3.5	3.5	1.5	4.5	2.0	5.0
7	5.26	0.00	3.5	3.5	1.0	4.5	2.0	4.5
Paddock total/mean	4.81	1.00	3.5	3.5	3.6	4.5	4.1	5.0
Annuity ($/ha/yr)			$40.06	$94.71	$34.11	$34.51	$34.41	$97.43
MIRR (%)			18%	26%	16%	15%	15%	21%
Pay-back period (years)			3 years	2 years	5 years	6 years	5 years	2 years

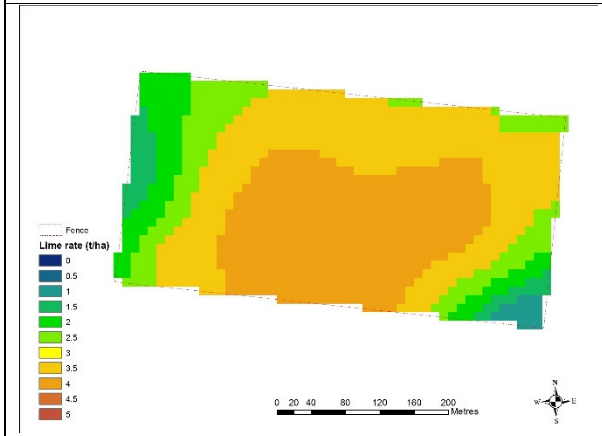
Note: the maximum allowable rate is 5.0 t/ha to avoid problems of over-liming (such as trace element deficiencies).

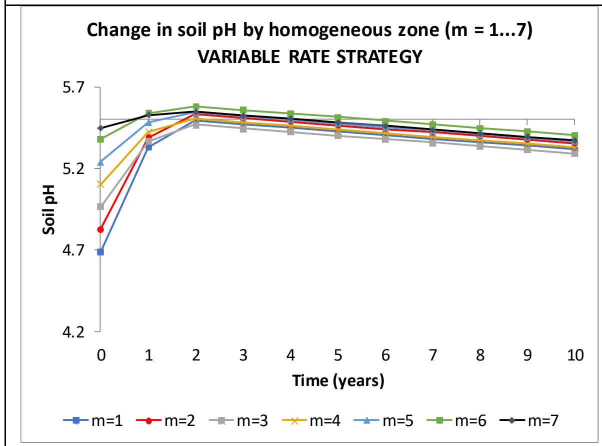
Table J.2. Economic and financial analysis for VR liming at Maroona: profit maximizing, acid sensitive rotation

	Present value ($ over 10 years) 31 ha paddock	Equivalent annual net benefits for paddock ($/yr)	Equivalent annual net benefits per hectare ($/ha/yr)
Benefits			
• Additional returns on farm (net)	$26,418	$3,872	$124.90
• Residual value of lime	$3,306	$485	$15.63
Costs			
• Laboratory analysis of soil samples	-$1,116	-$164	-$5.28
• pH mapping	-$217	-$32	-$1.03
• Effective lime cost, delivered	-$7,233	-$1,060	-$34.20
• VRA	-$551	-$81	-$2.61
Net benefits in current dollars	$20,607	$3,020	$97.43
MIRR (%)	21%	21%	21%
Pay-back period (years)		2 years	

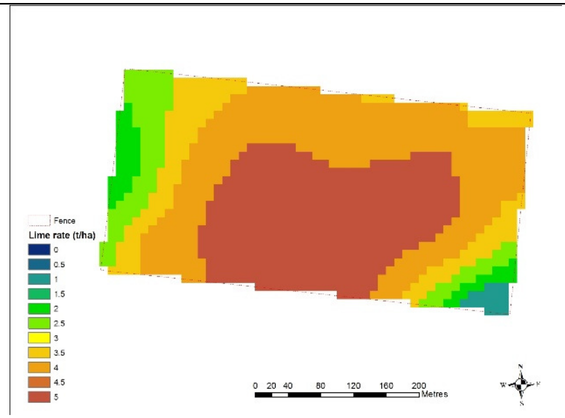
Figure K.1. VR Lime prescriptions for Newlyn

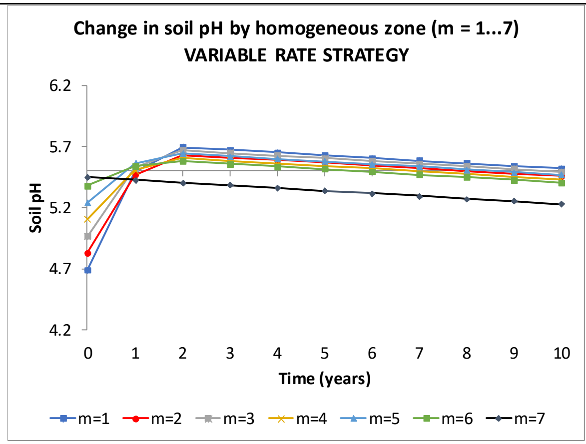
A. Target 5.5 liming rates for acid tolerant crop rotation (Scenario 3)



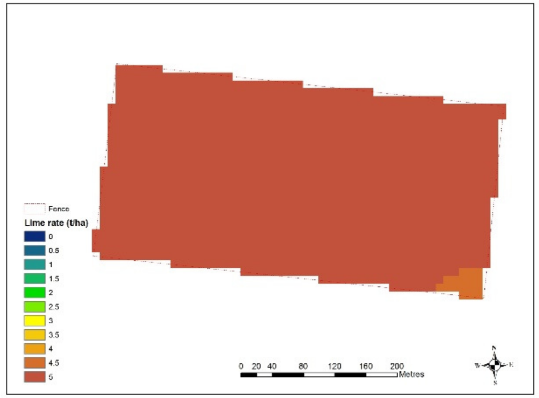


B. Profit maximising liming rates for acid tolerant crop rotation (Scenario 1)





C. Profit maximising liming rates for acid sensitive crop rotation (Scenario 1)



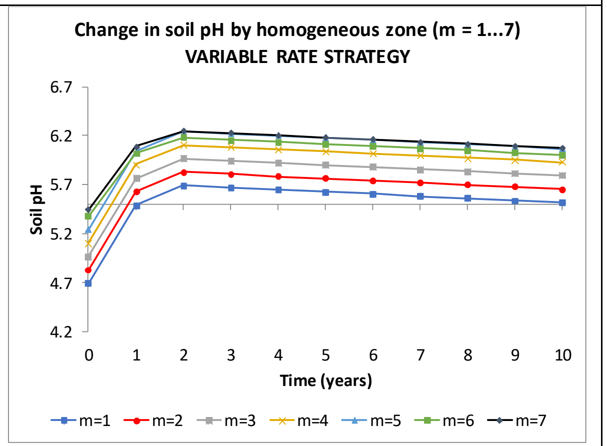


Table K.1 Lime prescription for the paddock at Newlyn (t/ha) @100% NV

	$pH_{Ca\ t=0}$ mid-point	Portion of paddock	Target 5.5 Uniform rate	Target 5.5 Uniform rate	Target 5.5 VRA	Profit maximizing Uniform rate	Profit maximizing VRA	Profit maximising VRA
Acidity management scenario			**4**	**4**	**3**	**2**	**1**	**1**
Information level			low	low	high	high	high	high
Rotation type			tolerant	sensitive	tolerant	tolerant	tolerant	sensitive
Homogeneous zone								
1	4.69	0.32	3.0	3.0	4.0	4.0	5.0	5.0
2	4.83	0.33	3.0	3.0	3.5	4.0	4.0	5.0
3	4.97	0.17	3.0	3.0	2.5	4.0	3.5	5.0
4	5.10	0.10	3.0	3.0	2.0	4.0	2.5	5.0
5	5.24	0.05	3.0	3.0	1.5	4.0	2.0	5.0
6	5.38	0.03	3.0	3.0	1.0	4.0	1.0	4.0
7	5.45	0.00	3.0	3.0	0.5	4.0	0.0	4.0
Paddock total/mean	4.87	1.00	3.0	3.0	3.2	4.0	3.9	5.0
Annuity ($/ha/yr)			$29.67	$75.56	$24.10	$24.55	$24.48	$81.25
MIRR (%)			17%	25%	14%	13%	13%	20%
Pay-back period (years)			4 years	2 years	6 years	6 years	6 years	2 years

Note: the maximum allowable rate is 5.0 t/ha to avoid problems of over-liming (such as trace element deficiencies).

Table K.2. Economic and financial analysis for VR liming at Newlyn: profit maximising, acid sensitive rotation

	Present value ($ over 10 years) 12 ha paddock	Equivalent annual net benefits for paddock ($/yr)	Equivalent annual net benefits per hectare ($/ha/yr)
Benefits			
• Additional returns on farm (net)	$8,893	$1,303	$108.62
• Residual value of lime	$1,270	$186	$15.51
Costs			
• Laboratory analysis of soil samples	-$432	-$63	-$5.28
• pH mapping	-$84	-$12	-$1.03
• Effective lime cost, delivered	-$2,782	-$408	-$33.98
• VRA	-$213	-$31	-$2.61
Net benefits in current dollars	$6,652	$975	$81.25
MIRR (%)	20%	20%	20%
Pay-back period (years)		2 years	