The value of information from research to enhance testing or monitoring of soil acidity in Western Australia[1]

M. O'Connell[a], A.D. Bathgate[a] and N.A. Glenn[b]

[a]Marketing Economics and Rural Adjustment
Agriculture Western Australia
Locked Bag No. 4
Bentley Delivery Centre WA 6983

[b]Agricultural and Resource Economics
Faculty of Agriculture
University of Western Australia
Nedlands WA 6907

Summary

The soil acidity research and extension program in Western Australia is made up of a number of projects, all of which are working towards the overall aim of helping farmers to manage soil acidity profitably. As a means of achieving this aim scientists are undertaking research to provide information that will enable farmers to better quantify potential yield losses due to subsoil aluminium, and to adopt liming strategies to prevent these losses. In this paper we present estimates of the value to farmers of information provided by this aspect of the research.

A bio-economic model is used to calculate the profitability of liming for different conditions and Bayesian Decision analysis is employed to estimate the payoff resulting from incrementally refining a lime strategy in three steps. The first step was the adoption of Strategy 1 which is a broad-based liming strategy. This reflects current practice in Western Australia where most lime is applied at 1 t/ha at around 10 year intervals. The second step (Strategy 2) is the adoption by farmers of more refined strategies, according to region, rotation and soil type. This would lead to higher expected profits but is not necessarily optimal. The third step (Strategy 3) is where a farmer is able to use information about the relationship between subsoil acidity and yield to refine the liming strategy on a paddock by paddock basis.

The results indicated that the value of current information aimed at improving management of soil acidity is high. However, the value of additional information generated by current research aimed at improving the certainty regarding yield response is lower. While moderately high in the low rainfall zone, the information is of less value to farmers in the medium and high rainfall zones. This may have implications for the future focus of acidity research and for defining a set of indicators for monitoring sustainability.

---

[1] An earlier report of this work was presented at the 43rd Annual Conference of the Australian Agricultural and Resource Economics Society, 20-22 January 1999, Christchurch, New Zealand.

Introduction

Soil acidification is an ongoing process in Western Australia. As a result of agricultural production, many light textured soils are acidifying to levels that are reducing crop and pasture production, or are likely to reduce production in the future. In some cases it is taking only 20-30 years from the time of clearing for acidity to reduce production by 5-10 percent (Dolling and Porter 1994). If left untreated, acidification is likely to affect a larger area of land than any other degradation problem in the State. It is estimated that agricultural production could be reduced by soil acidity on more than 10 million hectares of soils within the next 20 years (Porter and Miller 1998).

The major component of yield loss is an indirect effect of acidity, through the changed availability of nutrients and other elements. Low pH increases the availability of toxic elements, the main one of concern being aluminium (Al), while decreasing the availability of nutrients such of calcium, magnesium and phosphorus (Hunt and Gilkes 1992). Acidity also reduces yields by adversely affecting the nodulation, and hence nitrogen fixation of legumes. Therefore yield is affected by a combination of nutrient deficiency and toxicity. The most common strategy used to manage soil acidity is the application of lime, which is an abundant alkali and can be mined at relatively low cost.

However, decisions regarding the timing of application and the rate of lime are complicated by a number of factors. These include the slow onset of soil acidity, difficulties in detecting the problem, and time lags of up to several years before soil pH and yields respond to lime applications. In addition, the relationships between soil acidity, toxic elements and yield are complex, and consequently responses to lime on acid soils are unpredictable (Lightfoot 1990). For any given situation it is not always possible to be sure of a) whether any yield loss is occurring, b) the rate of lime necessary to fix the problem and c) the time lag between application and response. Furthermore, pH and Al levels for a particular soil can be extremely variable, both down the soil profile, and between individual sites within the paddock (Whitten and Ritchie 1990). As a consequence of these and other factors, yield responses to liming can be observed at one site, while no response is evident at a similar site. Such uncertainties mean that many farmers are unsure of the benefits of lime and are therefore reluctant to apply it (Lamond 1990), while those that do apply lime may sometimes question if it has really improved production (e.g. Lance 1998). These issues are particularly relevant to the problem of subsoil acidity. Whereas topsoil acidity can be relatively easily identified and corrected by applying lime, problems in the subsoil are more difficult to measure and ameliorate (Rengel and Diatlof 1998).

In response to these issues research is being undertaken in Western Australia that aims to better characterise the Al toxicity of the subsoil to reduce the uncertainty regarding the yield response from lime application. The aim of this paper is to estimate the value of this information to farmers, taking into account the degree of uncertainty in the decision problem.

A bio-economic model, Optlime, was used to generate data for a range of scenarios. The model describes the essential biological features and interactions of the system, as well as the economic benefits and costs of liming. The data generated by Optlime was used to estimate the value to farmers of research information. The framework used to estimate the value of the research information is based on Bayesian Decision Theory.

Method

Liming strategies

Three liming strategies were considered in the analysis (apart from the strategy of no liming). The first is the adoption by farmers of the most common liming practice in WA, where lime is applied at about 1 t/ha every 10 years (Strategy 1). The second case is the adoption by farmers of more refined strategies, where the rate of lime is adjusted according to soil type, rotation and rainfall (Strategy 2). While this results in more specific recommendations, there are many instances where it is sub optimal. The third case is where a farmer is able to further refine a liming strategy by assessing the Al toxicity of a paddock and apply a lime rate which is closer to the optimum (Strategy 3). These strategies are shown in Figure 1.

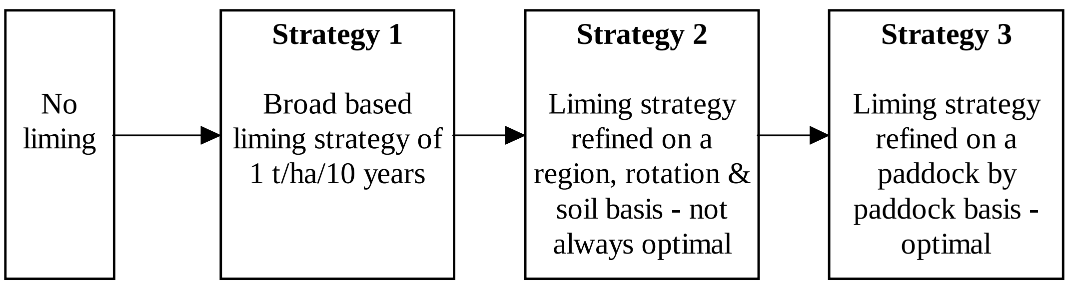

Figure 1. Steps involved in refining a liming strategy toward the optimum.

Without any further research, information currently available enables farmers to move from Strategy 1 to Strategy 2. Therefore over the medium term it is expected that most will make this shift. The difference in expected profit between these two strategies provides a measure of the value of past research. Additional information generated by the research currently under way will enable farmers to adopt Strategy 3, and the difference in profit between Strategy 2 and Strategy 3 is the marginal value of the information from current research, which s largely aimed at improving measurements of Al in the subsoil.

Identification of current knowledge about subsoil aluminium toxicity

The relationship between soil pH and Al concentration has been determined for several soil types in Western Australia (e.g. Dolling et al., 1990), and critical Al concentrations estimated. (The ‘critical level’ is that used by biologists and is the concentration required to reduce yield by 10 percent). Current knowledge of the levels of Al that are toxic to annual plants is outlined in Table 11 in the Appendix. These critical levels are estimates and should be used as a guide only (Diatlof, unpublished). Table 12 in the Appendix shows the critical pH for a range of agricultural plants. Critical levels of aluminium are also provided where available. The critical levels imply nothing about the economics of managing pH or Al, and the optimum levels may be above or below those defined as “critical”.

While estimates of critical pH for many crop and pasture species are readily available, less work has been done to estimate critical Al concentrations. This is due, in part, to the complex nature of the relationship between Al concentration and yield loss, so that a simple measure of Al in the subsoil is unlikely to be sufficient to determine whether crop yield will be adversely affected (Carr 1992). Topsoil measurements of aluminium toxicity are even more difficult to interpret as the Al is often complexed with organic matter, and therefore not toxic to plants. Consequently yield losses due to Al are highly variable and Al tests are used infrequently for decision support (Diatlof, pers. comm).

While there is no doubt that Al toxicity can cause yield losses in acidic soils, the difficulty is in identifying those soils on which yield is adversely affected. Consequently there will be cases where lime is applied unnecessarily, and instances of yield losses occurring due to undiagnosed Al toxicity. Current research is aimed at reducing the uncertainty of yield response to subsoil acidity.

Decision framework for estimating the value of information

Provision of new information reduces the uncertainty regarding the characteristics of the topsoil and subsoil and therefore better establishes the rate of lime required. It is expected that the new information generated by the research will increase the profitability of managing soil acidity as the levels of lime applied will be nearer to the optimum levels. The improvement in profitability made possible by this new information will be referred to here as the "value of information".

Bayesian Decision Theory provides the basis of a framework to determine the value of reducing uncertainty about the impact of subsoil Al on yields and the increases in yield resulting from liming. A simplified outline of the analysis undertaken in this study is described below.

The first step in Bayesian decision analysis is to establish the current level of knowledge. For example, consider a farmer whose soil pH has been tested and found to be 4.5 in the topsoil and 4.0 in the subsoil. Previous soil surveys for this soil type have indicated that approximately 30 percent of the subsoil can be classed as low Al toxicity (less than 3 mg/kg at pH of 4.0) and 70 percent as high (more than 3 mg/kg at pH of 4). However current information does not allow the Al toxicity of a particular paddock to be readily identified.

In decision theory the various scenarios (e.g. Al toxicities) that are possible are called 'states', while the probabilities of each of the states with our current knowledge are called 'prior' probabilities. Following Anderson et al. (1977), each state is represented here by θ_i, while prior probabilities for each state are represented by $P(\theta_i)$. The states and prior probabilities for this example are presented in Table 1.

Table 1. Prior probabilities and expected equivalent annual value (EAV).

State, θ_i	Prior probability $P(\theta_i)$	EAV 1 t/ha/10 years	EAV 2 t/ha/10 years
Low aluminium	0.3	100.00	85.00
High aluminium	0.7	50.00	75.00
	Expected EAV	65.00	78.00

Now, assume that for a subsoil that is highly Al toxic, the equivalent annual value (EAV) of the cashflow over a 10 year period is $50/ha if lime is applied at 1 t/ha/10 years, and $75/ha if 2 t/ha/10 years is applied. Similarly, if the subsoil has low Al toxicity, assume the EAVs are $100/ha for 1 t/ha/10 years of lime, and $85/ha for 2 t/ha/10 years. The expected EAV for each liming strategy is the sum of the EAVs weighted by the prior probabilities (Table 1).

Faced with this information about the probabilities of Al toxicity and cash flow, the better option is to apply lime at 2 t/ha/10 years because the expected EAV is highest ($78/ha). In decision theory, the strategy that has the highest expected payoff[2] based on current knowledge is called the 'prior optimal act' (Hardaker et al., 1997). While this strategy gives the highest expected EAV, in some cases it would be more profitable to apply 1 t/ha/10 years. However the information required to target the case where 1t/ha is more profitable is unavailable.

Now assume that because of new research, it becomes possible to more accurately identify potential yield losses due to subsoil aluminium toxicity. Combined with a soil test for Al, this information will allow the farmer to more accurately identify the optimal liming strategy. This new technology will correctly identify the severity of Al toxicity 95 percent of the time, with a 5 percent chance that the result returned will be wrong. These new probabilities are called 'likelihoods' and have the notation $P(z_i \mid \theta_i)$, which is conditional probability of event z_i given state θ_i'. In this case the events, z_i, are the Al toxicities (i.e. Al test results). This new information is given in Table 2.

Table 2. Probabilities of various aluminium test results given actual levels.

State θ_i	Prior probability $P(\theta_i)$	Likelihoods, $P(z_i \mid \theta_i)$: z_1 (test result low)	z_2 (test result high)
Low aluminium	0.3	0.95	0.05
High aluminium	0.7	0.05	0.95

Thus it will now be possible for the farmer to test the soil for Al and, using the information about the relationship between subsoil acidity and yield, decide whether to implement a 1 or a 2 t/ha/10 years liming strategy. There is then a higher probability that the farmer will implement the correct strategy, so expected profitability will improve. The increase in the expected return is the value to the farmer of this new information.

[2] The payoff is expressed here in expected monetary terms but it may also include an adjustment for risk premiums.

To begin with we need to calculate how often particular Al test results will occur. This is done by first calculating the probabilities of state θ_i and Al test result z_i occurring together. These are called joint probabilities, P(z_i and θ_i), and are calculated thus, $P(\theta_i) * P(z_i \mid \theta_i)$. Joint probabilities for this example are presented in Table 3. Now by summing the joint probabilities in each column of Table 3 it is possible to establish the probability of a certain test result, $P(z_i)$.

Table 3. Joint probabilities.

State θ_i	**Prior probability $P(\theta_i)$**	**Joint probabilities, P(z_i and θ_i)**	
		z_1 (test result low)	**z_2** (test result high)
Low aluminium	0.3	0.285	0.015
High aluminium	0.7	0.035	0.665
Probability of test result z_i, $P(z_i)$		**0.32**	**0.68**

So given the prior probabilities and likelihoods, 32 percent of all Al tests undertaken will return a low result, and 68 percent will return a high result.

Having established the frequency of Al test results, it is now necessary to determine how often we expect to apply a particular liming strategy on each soil type. These are called 'revised' probabilities, identified by the notation $P(\theta_i \mid z_i)$. Revised probabilities give the probability of state θ_i given event z_i, calculated as P(z_i and θ_i) / $P(z_i)$. These are shown in Table 4.

Table 4. Revised probabilities

State θ_i	**Prior probability $P(\theta_i)$**	**Revised probabilities, $P(\theta_i \mid z_i)$**	
		z_1 (test result low)	**z_2** (test result high)
Low aluminium	0.3	0.891	0.022
High aluminium	0.7	0.109	0.978
Sum of revised probabilities		1	1

The revised probabilities tell us that if the test result returned is low, there is an 89 percent chance that the soil Al toxicity is indeed low, and an 11 percent chance that it is high. Similarly if the test result is high, then there is a 98 percent chance that the soil is in fact highly Al toxic, and a 2 percent chance that it has low Al toxicity.

This means that when the farmer conducts a soil test to choose between the two liming strategies, if the test result is low then 89 percent of the time the better liming strategy will be applied while, if the test result is high, the better strategy would be applied 98 percent of time. With this information it is possible to calculate the expected EAV given the new information (Table 5).

Table 5. Expected EAVs resulting from the new information.

	Aluminium test results	
	z_1 (test result low)	**z_2** (test result high)
EAVs from Table 1		
Low aluminium	100.00	85.00
High aluminium	50.00	75.00
Revised probabilities from Table 4		
Low aluminium	0.891	0.022
High aluminium	0.109	0.978
GMs * revised probabilities		
Low aluminium	89.10	1.87
High aluminium	5.45	73.35
Expected EAV	94.55	75.22

So we have estimated that the expected EAV following a low test result is $95/ha, while with a high test result, the expected EAV is $75/ha. Recall from Table 3 that the probabilities of low and high test results were established to be 32 percent and 68 percent respectively. By using these probabilities it is possible to now calculate the expected EAV from the 'revised optimal act'. This is the weighted average of the expected EAV from Table 5, where the weighting is from the probabilities of test results as presented in Table 3. Therefore the expected EAV from the revised optimal act is $81/ha (Table 6). By comparing this with the EAV from the prior optimal act, which was $78.00, it is estimated that the value of information provided by the soil test is $3/ha (Table 6).

Table 6. Calculation of EAV of revised optimal act and value of information of Al test.

	Probability of test result z_i, $P(z_i)$		**EAV ($/ha)**
Probability of low test result, $P(z_1)$	0.32	EAV with low test result	95
Probability of high test result, $P(z_2)$	0.68	EAV with high test result	75
		EAV from revised optimal act	**81**
		GM from prior optimal act	**78**
		Difference	**3**

Data source

A bio-economic model, Optlime, was used to estimate the profitability of liming under a range of scenarios. Optlime models the response of crop yield to soil pH, subsoil Al and lime application over a 30 year period (Sandison and Bathgate 1995, unpublished). The soil profile is divided into three layers and the mass balance of lime is calculated for each layer to determine its movement down the soil profile. The change in discounted cashflow resulting from liming can be calculated for a range of crop and pasture rotations. The model has been calibrated for a number of soil types in three rainfall regions. The model is spreadsheet based and uses a non-linear solving algorithm to optimise lime rate.

For the purpose of this analysis, Optlime was modified to a 10 year cash flow. This was done because it is assumed that even without research, farmers would continue to refine their lime applications over time toward optimal strategies. This process of farmer experimentation and refinement is likely to take less than 30 years.

Soil types and rainfall regions

Four broad soil classifications were considered in this analysis. They were deep sands, duplexes, loams and clays. The areas of each of these soil types were estimated from a database of Western Australian soils (Perry, unpublished).

The deep sand classification refers primarily to good light sandplain (e.g. Eradu sandplain), heavier sandplain (e.g. yellow earths, including wodjil soils) and the leached sands (e.g. West Midlands). The distinction between loams and duplexes is not always clear. For the purpose of this analysis the duplex classification refers only to soils that have a sandy topsoil over a clay subsoil, while soils with a loamy topsoil over a clay base are grouped with loams. Included in the duplex classification are large areas of the South Coast and West Midlands, while the loam classification includes much of the stronger clayey soil types to be found throughout the central, northern, eastern and south eastern wheatbelt along with the Avon and Chapman Valleys and Great Southern. Within the loam classification are some hard-setting loams that would often be considered clays. For this reason, the area classified as clay in this analysis is not extensive and mostly consists of small areas around Dalwallinu, Southern Cross and Salmon Gums (Perry, unpublished). Alkaline soils were excluded from the analysis as were other soils of minor agricultural importance. The total area of soils considered was just under 10 million hectares, out of a total of 15 million hectares in the wheatbelt.

The WA agricultural region was divided into three rainfall regions, corresponding to Agriculture Western Australia's Crop Variety Recommendation Areas: low (less than 325 mm annual average rainfall), medium (325 to 450 mm) and high (more than 450 mm) rainfall zones (see Figure 2).

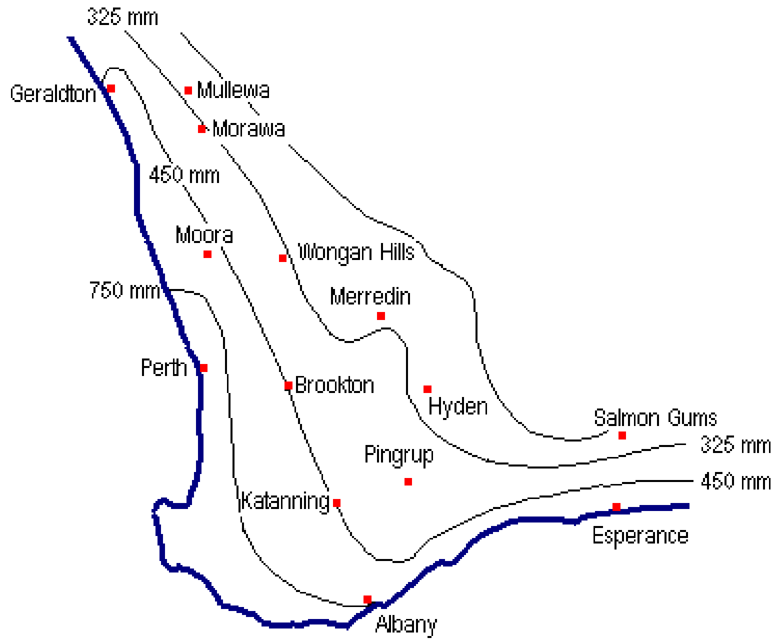

Figure 2. Rainfall zones in south-west of Western Australia

Key assumptions used in the analysis

Key assumptions used in the analysis are shown in Table 13 in the Appendix. The grain prices used reflect long term estimates (I. Wilkinson, pers comm) and as such may differ somewhat from current season prices. Appropriate transport and selling costs were deducted from the grain prices, depending on grain type and transport distance. Variable costs of production are set at typical levels for the specified regions of the Western Australian wheatbelt. Limesand from Western Australian coastal dune deposits typically costs about $7/tonne (plus transport), while the lime spreading costs reflect those charged by contractors (D. Holdsworth, pers comm).

Due to the number of different scenarios assessed, the biological assumptions used in the analysis are too numerous to present here. For example, each soil type within a rainfall region has its own unique soil properties, and on that soil type each crop in each rotation has its own yield potential and acidification rate. Details of the biological assumptions used are available from the authors in a technical appendix.

Analyses conducted

Two sets of rotations were used to calculate the profitability of liming under the range of research outcomes. The first set of rotations are somewhat reflective of current practice. They have been derived after consulting Australian Bureau of Statistics data, and discussions with people familiar with farming practices in different regions (V. Stewart, pers comm; A. Herbert, pers comm). The second set of rotations are what could be described as profit maximising. They are generally continuous crop or crop dominant with a low proportion of pasture. These rotations are outlined in Table 13 in the Appendix.

Scenarios were defined in terms of soil type, rainfall region and level of soil acidity. For each rainfall region and soil type, three levels of acidity (pH) were considered. These are shown in Table 7.

Table 7. Levels of acidity considered in the analysis.

pH (topsoil, subsoil)	Comments
5.3, 4.9	Little or no yield loss due to acidity
4.8, 4.4	Yield loss likely.
4.3, 3.9	Significant yield loss occurring.

Within each scenario, three aluminium concentrations were considered. The aluminium response curves are shown in Figure 3, while a description of the aluminium concentrations is outlined in Table 8.

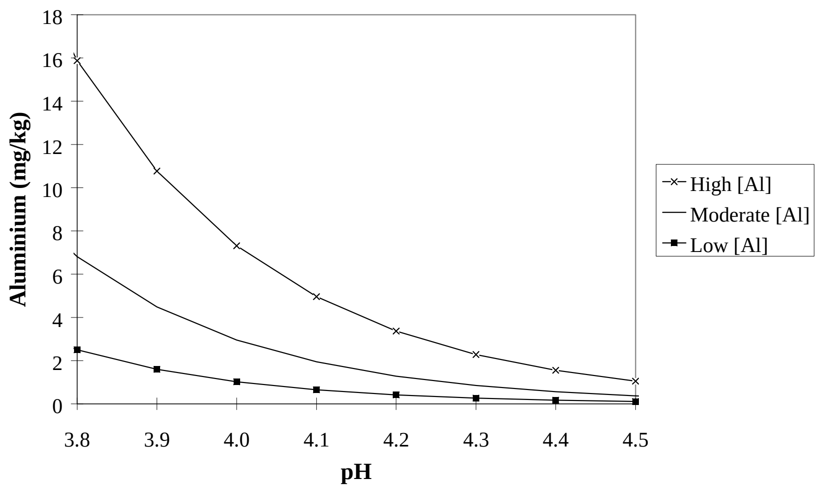

Figure 3. Al concentration, verses soil pH for the three Al levels used in the analysis.

Table 8. Description of aluminium response curves considered in the analysis.

Subsoil Al	Concentration of aluminium at pH 4	Comments
Low	< 2 mg/kg	Not toxic
Medium	2-5 mg/kg	Toxic to Al sensitive plants
High	> 5 mg/kg	Toxic to most Al tolerant plants

Data generation and sensitivity analysis

In total 36 different scenarios were considered (4 soils * 3 regions * 3 pH = 36). Within each scenario there were 3 levels of aluminium. These scenarios were analysed using both the current practice and profit maximising rotations. For each scenario, a modified version of Optlime was used to calculate average gross margins over 10 years that would result from 6 different liming rates, with the rates being 0, 1, 2, 3, 4 and 5 t/ha of lime every ten years. Results from these model runs were then subject to a value of information analysis based on Bayesian Decision Theory.

The cashflow was calculated over 10 years because it was assumed that the benefits of the Al test to a farmer would be limited to this period. After the initial application of lime farmers would be able to adjust the rate of the next application given the initial yield response. This new rate is likely to be an improvement of the initial rate in many cases. This assumption may lead to the value of information being underestimated, because the Al test may reduce the incidence of errors in the 2^{nd} application. However the net benefits of reducing this error is likely to be small. To assess the importance of this, the analyses were repeated using the unmodified Optlime with its 30 year cash flow.

For each soil type and rainfall region, the annual net benefit of adopting Strategy 1 was the difference in expected EAVs of applying no lime and adopting Strategy 1. Bayesian decision theory was then used to estimate the value of information from research. The prior optimal act was taken to represent the case where farmers are able to refine lime applications to some extent, but still lack detailed information about the extent of soil acidity. The revised optimal act was taken to represent the case where a farmer is able test the soil for pH and Al, and use this information, together with information about likely yield losses, to refine a liming strategy on a paddock by paddock basis.

Estimation of prior probabilities and likelihoods

The prior probabilities of topsoil and subsoil pH were estimated from trial data gathered from many sites in Western Australia (M. Whitten; C. Gazey, unpublished data). These probabilities are outlined in Table 14 in the Appendix.

Insufficient data exists to characterise the distribution of subsoil Al toxicity in Western Australian. However, a wide range of measurements are commonly observed. For this reason soils were assumed to be of low, moderate and high toxicity with equal frequency.

The likelihood of accurately identifying the optimal strategy was assumed to be 90 percent. Previous work aimed at developing means to quantify the severity of likely yield losses due to acidity has at most been able to explain 95 percent of the variability in grain yield. However, the amount of variability explained by this same test has been as low as 30 percent (Carr et al., 1991). Therefore, it is realistic to assume that even if the methods of quantifying acidity were significantly improved, a 10 percent error rate might still occur.

Results and Discussion

Estimates of the benefits of refining liming rates are shown in Table 9 and Table 10. As previously described the benefit of Strategy 2 is the value of information from past research. The benefit of moving from the Strategy 2 to Strategy 3 is the estimated value to farmers of current research aimed at reducing the uncertainty of yield response to subsoil acidity. The results presented are only for very acidic scenarios. Under the less acidic scenarios the values of information were lower. Hence, the results presented represent an upper bound.

Table 9. Incremental benefits of refining a liming strategy using current practice rotations.

	Incremental benefits of adopting liming ($/ha/year)		
	Strategy 1	**Strategy 2**	**Strategy 3**
Low rainfall zone			
Deep sand	15	14	4
Clay	8	8	2
Medium rainfall zone			
Deep sand	25	35	3
Clay	12	19	2
High rainfall zone			
Deep sand	6	7	3
Clay	7	21	0

For all scenarios initial pH was 4.3 in topsoil, 3.9 in subsoil. Strategy 1: 1t/ha/10 years; Strategy 2: refined by soil type, rotation and region; Strategy 3: refined by using information about likely yield losses and soil test results.

Table 10. Incremental benefits of refining a liming strategy towards that which is optimal using profit maximising rotations.

	Incremental benefits of adopting liming ($/ha/year)		
	Strategy 1	**Strategy 2**	**Strategy 3**
Low rainfall zone			
Deep sand	31	35	3
Clay	24	36	4
Medium rainfall zone			
Deep sand	52	73	3
Clay	31	61	2
High rainfall zone			
Deep sand	16	26	2
Clay	7	20	0

For all scenarios initial pH was 4.3 in topsoil, 3.9 in subsoil. Strategy 1: 1t/ha/10 years; Strategy 2: refined by soil type, rotation and region; Strategy 3: refined by using information about likely yield losses and soil test results.

Under acidic conditions, adoption of Strategy 1 (1 t/ha/10 years) leads to a large increase in profit. The benefits of adopting Strategy 1 are typically higher where profit-maximising rotations are used. This is because profit maximising rotations tend to contain a higher proportion of acid sensitive crops (e.g. canola and chick peas). Similarly, the results indicate that further refinement of liming from Strategy 1 to Strategy 2 can lead to large increases in profit. Again, the increases in profit tend to be positively correlated to the potential rotational gross margins.

In contrast to the benefits of adopting Strategy 1 and Strategy 2, the incremental values of adopting Strategy 3 are similar for all rotations. In addition, the absolute increases in profitability are much lower. Typically the values range from $1 to $4/ha/year, and tend to be higher in the low rainfall zone.

The benefits of fine tuning decisions regarding lime rate may appear low, especially given the importance that is placed on subsoil Al and pH in the literature. One might assume that because subsoil pH and Al levels are important contributors to yield loss that more detailed information about them would be highly valuable. However, expected EAVs from acidic soils tend to plateau as lime application increases, and there are only small differences in profit across a wide range of lime rates (e.g. Figure 4). This is explained by the relationship between lime application and yield response of the crop or pasture. Marginal increases in yield diminish rapidly above application of 1t/ha. Therefore the effect of the information is to move the farmer's choice along a flat payoff curve. Furthermore, the new information that is gathered only decreases uncertainty and does not eliminate it. Therefore the liming strategy adopted in some cases will not be optimal. This has the effect of reducing the expected payoff.

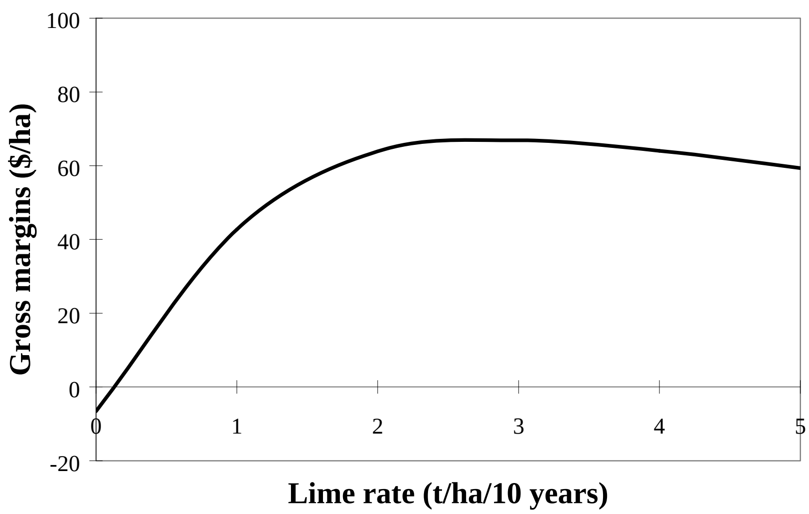

Figure 4. Expected gross margins from a deep sand in the low rainfall zone growing a wheat - canola - wheat - lupin rotation. Subsoil is moderately Al toxic. Starting pH: 4.3 (top), 3.9 (sub).

An unexpected result of the analysis is that the information provided by the soil test is of most value to farmers in the low rainfall region. This result occurs because in the higher rainfall zone the rotations used in the calculations contain a high proportion of pasture. Pasture-based enterprises are generally less profitable than crop. Under the most severely acid situations, the simulated increase in productivity from limed pasture was insufficient to cover the cost of applying lime. In some cases there was simply no strategy that was profitable, including doing nothing.

The profitability of liming (Strategy 1 and 2) in the high rainfall is lower than expected, when compared to the low and medium rainfall zone. This result is explained by the higher cropping frequency in the low rainfall and medium rainfall zones. As pasture is less affected by subsoil acidity, at least in economic terms, the benefits of liming are greater in crop-dominated farming systems.

It needs to be emphasised that the values of adopting Strategy 3 are values of information that result from measuring Al once, and using this information to refine the management of soil acidity. This first measurement has removed most of the uncertainty regarding potential yield losses due to acidity. Although further measurement of Al will refine this knowledge, the extra value of doing so will diminish further.

The results of this study do not imply that the benefits of soil acidity research are low in general. While it is true that information that allows the farmers to closely refine lime rates to the optimal strategy produces small gains, the information that allowed the farmer to move from the broad strategy 1 to the refined strategy 2 was a highly valuable outcome of past research on soil acidity. In addition, although the value of information that allow adoption of optimal liming strategies is low on a per hectare basis, it is applicable to a large area of the Western Australian wheatbelt (potentially 10 million hectares). The benefits of the research could be substantial if a significant number of farmers adopt the test. Having said that, the low payoff that results from this technology is unlikely to encourage a large number of farmers to adopt.

The results of this study also have implications for the growing body of literature devoted to sustainability indicators. Of the many sustainability indicators that have been proposed for agricultural systems (e.g. RIRDC 1997), monitoring of subsoil pH and Al appear to be among the more practical for farm management. However, it is unlikely that farmers will regularly monitor indicators of sustainability unless the information gathered can be used to improve management. Continued monitoring will result in smaller and smaller increases in profit, such that the benefit of monitoring will soon be less than the cost of doing so. Instead, subsoil acidity and Al might be measured once in order to improve understanding and refine measurement, and then not again for a number of years (Glenn and Pannell, 1998).

Conclusion

The per hectare benefit to farmers of adopting a broad based liming strategy on acidic soils (e.g. 1 t/ha/10 years) is high. Similarly, past research that has allowed some refinement to liming strategies has been valuable. However, the additional value to Western Australian farmers of information that allows detailed specification of optimal liming strategies is low (between $1 and $4/ha/year). This result is robust for a range of assumption regarding the crops grown, and the period over which the benefits accrue.

The aggregate benefits of the work will depend on a number of factors including the extent of adoption of an appropriate Al test. The low payoff calculated in this analysis is unlikely to be sufficient to encourage widespread adoption, so the total benefits may be low. This analysis suggests that Al (and perhaps pH) is unlikely to be monitored closely or frequently by farmers, because the information collected from repeated monitoring will be of low value in adjusting management decisions.

Acknowledgements

The authors are grateful to the members of the Western Australian Soil Acidity Research team for their involvement in this analysis and the development of Optlime, and to Associate Professor David Pannell from the University of Western Australia for reviewing the paper.

This research is supported by growers through the Grains Research & Development Corporation in partnership with Agriculture Western Australia.

References

Anderson, J.R., Dillon, J.L. and Hardaker, J.B. (1977). Agricultural Decision Analysis. Page 50 - 64. Iowa State University Press.

Carr, S.J. (1992). Development of a soil test for the diagnosis of subsoil aluminium toxicity in yellow earths in Western Australia. Ph.D. Thesis. University of Western Australia, Department of Soil Science and Plant Nutrition.

Carr, S.J., Ritchie, G.S.P. and Porter, W.M. (1991). A soil test for aluminium toxicity in acidic subsoils of yellow earths in Western Australia. Australian Journal of Agricultural Research 42: 875 - 892

Diatlof, E. (unpublished). Critical tests for aluminium in soils. Table of critical levels of aluminium with various methods of measurement.

Dolling, P., Porter, W.M. and Robson, A.D. (1990). Soil pH and aluminium and their spatial variability in Western Australian acidic soils. Australian Journal of Experimental Agriculture 30: 637 - 643

Dolling, P., Porter, W.M. and Robson, A.D. (1991). Effect of soil acidity on barley production in the south-west of Western Australia 2. Cereal genotypes and their response to lime. Australian Journal of Experimental Agriculture 31: 811 - 818

Dolling, P. (1994). Critical levels of soil acidity for cereals and rates of acidification. GRDC Project Number 72/8061 (DAW 42W) Final Report. Department of Agriculture Western Australia.

Dolling, P and Porter, W.M. (1994). Acidification rates in the central wheatbelt of Western Australia. 1. On a deep yellow sand. Australian Journal of Experimental Agriculture 34, 1155 - 64

Evans, J., Dear, B. and O'Connor, G.E. (1990). Influence of an acid soil on the herbage yield and nodulation of five annual pasture legumes. Australian Journal of Experimental Agriculture 30: 55 - 60.

Glenn, N.A. and Pannell, D.J. (1998). The Economics and Application of Sustainability Indicators in Agriculture. Contributed Paper at the 42nd Annual Conference of the Australian Agricultural and Resource Economics Society, Armidale NSW, 19-21 January 1998.

Hardaker, J.B., Huirne, R.B.M. and Anderson, J.R. (1997). Coping with risk in Agriculture. CAB International, New York, USA

Hunt, N. and Gilkes, B. (1992). Farm Monitoring Handbook. Pages 187 - 212. The University Of Western Australia.

Lamond, M. (1990). The farmers' perspective. In: Soil Acidity Workshop: Avon Districts Agricultural Centre, Northam, April 11, 1990. Compiled by Fionnula Frost.

Lance, R. (1998). On - Farm Treatment Of Acid Soils. Southern Tablelands of NSW. In: Proceedings of the 1998 National Soil Acidification Conference. 15 - 17 July 1998. Hyatt Regency Coolum, Sunshine Coast, Queensland, Australia.

Lightfoot, L. (1990). Predicting lime response. In: Soil Acidity Workshop: Avon Districts Agricultural Centre, Northam, April 11, 1990. Compiled by Fionnula Frost.

Perry, M. (unpublished). Soils database prepared for analysis of soils suitable for grain legumes.

Porter, W.M. and Miller, A. (1998). Lime use targets for Western Australia. In "Western Australia Soil Acidity Research and Development Update 1998". Ed A. Miller, Agriculture Western Australia.

Rengel, Z. and Diatlof, E. (1998). Modelling Yield Losses Due To Subsoil Acidity. Western Australia Soil Acidity Research and Development Update 1998. Ed: A. Miller. Pages 34 - 39. Agriculture Western Australia, Northam.

Rural Industries Research and Development Corporation (1997). Sustainability indicators for agriculture - Introductory guide to regional/national and on-farm indicators. RIRDC Publication No. 97/72.

Whitten, M. and Ritchie, G. (1990). Soil tests for Al toxicity in topsoils. In: Soil Acidity Workshop: Avon Districts Agricultural Centre, Northam, April 11, 1990. Compiled by Fionnula Frost.

Yeates, J. (1988). Soil acidity and productivity of sub. clover pasture. Journal of Agriculture, Western Australia 29:1, 20 - 24

Appendix

Table 11. Current recommendations for critical soil aluminium concentrations. From Diatlof (unpublished).

Aluminium test	Not toxic to plants (Too low to measure)	Toxic to most Al-sensitive plants	Toxic to most Al-tolerant plants
0.01 M $CaCl_2$ "plant available"	< 2 mg kg^{-1}	2-5 mg kg^{-1}	> 5 mg kg^{-1}

Table 12. Critical aluminium concentration and pH for a range of crop and pasture species.

Species	Critical Al concentration (mg/kg)	Critical pH ($CaCl_2$)	Source
Truncatula medics		5.5 - 5.8	Hunt and Gilkes 1992
Polymorpha medics		4.8 - 5.2	Hunt and Gilkes 1992
Murex medics	> 2 - 5 **	4.5 - 4.8	Evans et al., 1990; Hunt and Gilkes 1992
Barley	> 3 - 4	< 4.5	Dolling et al., 1991
Wheat	> 2 - 5 *	< 4.3	Carr et al., 1991; Dolling 1994
Sub clover		< 4.3	Yeates 1988
Serradella and lupins		4.0 - 4.3	Hunt and Gilkes 1992
Oats and triticale		4.0 - 4.3	Hunt and Gilkes 1992
Cereal rye		3.9 - 4.2	Hunt and Gilkes 1992

* estimated from original data which was expressed as μM in soil solution
** converted from % of CEC

Table 13. Key assumptions

	Prices ($/t for grain, $/clean kg for wool)	Variable costs ($/ha for crops and pasture, $/DSE for sheep)		
		Low rainfall zone	Medium rainfall zone	High rainfall zone
Wheat	200	130	150	170
Barley	195	120	140	160
Lupins	190	100	125	150
Chick peas	320	110	135	155
Canola	365	160	180	200
Wool	6.50			
Pasture		5.00	6.50	7.50
Sheep husbandry		5.00	6.00	7.00

Current practice rotations used for calculating profitability of liming from Optlime

	Low rainfall zone	Medium rainfall zone	High rainfall zone
Deep sand	4PWCWLWLW	7PWCWLWLW	PPPP
Duplex	4PWCWLWLW	7PWCWLWLW	10PWCBLW
Loam	4PWCWCpWCpW	7PWCWCpWCpW	10PWCBCpW
Clay	4PWCW	4PWCW	10PWCBCpW

Profit maximising rotations used for calculating profitability of liming from Optlime

	Low rainfall zone	Medium rainfall zone	High rainfall zone
Deep sand	WCWL	WCWL	4PWLW
Duplex	WCWL	WCWL	4PWLWC
Loam	WCWCp	WCWCp	4PWCpWC
Clay	WWCp	WWCp	4PWCpW

Lime spreading cost structure *

Lime rate (t/ha)	Cost ($/t)
0.25	34.00
0.50	17.00
1.00	8.50
1.25	8.00
1.50	7.50
2.00	7.00
3.00	6.50
4.00	6.00

Key to symbols

W	Wheat
C	Canola
L	Lupins
Cp	Chick peas
P	Pasture

Lime cost at pit ($/t)	7.00
Freight rate ($/km/t)	0.10

* supplied by Mr D. Holdsworth of D & D Transport of Wyalkatchem, WA

Table 14. Assumed distribution of soil pH.

Initial subsoil pH range - proportions	Initial topsoil pH range - proportions					
	< 4.0	**between 4.0 and 4.5**	**between 4.5 and 5.0**	**between 5 and 5.5**	**> 5.5**	**Total**
less than 4.0	0%	2%	5%	0%	0%	**7%**
between 4.0 and 4.5	0%	17%	29%	12%	0%	**57%**
between 4.5 and 5.0	0%	2%	21%	5%	0%	**29%**
between 5 and 5.5	0%	2%	0%	0%	0%	**2%**
greater than 5.5	0%	2%	2%	0%	0%	**5%**
Total	**0%**	**26%**	**57%**	**17%**	**0%**	**100%**