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A dynamic model of optimal lime application for wheat production in Australia*

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Soil acidification due to crop removal and the use of acidifying fertilisers reduce land productivity in many agricultural systems worldwide. The most common remedy is to apply lime to the soil surface. An alternative approach is to incorporate lime into the sub-soil. This is a more expensive option, but it substantially reduces the time required to reduce acidity in the sub-soil horizons. This paper presents a dynamic optimisation model to determine optimal rates, frequency and methods of lime application for a wheat monoculture system in the northern part of the Western Australian wheatbelt. Results show that optimal application rates depend on rainfall levels and soil-acidity conditions. The net present value of profit is not sensitive to the frequency of lime application. Incorporating lime into the sub-soil increases the net present value of profit, but only by a small amount: two to four per cent in most scenarios modelled. In the process, sub-soil lime application reduces both the optimal lime application rate and the time required for the soil pH to increase to a target level.

Key words: dynamic optimisation, lime application, soil acidity, wheat.

1. Introduction

Approximately 50 per cent of arable land worldwide is acidic (Zheng 2010; Li *et al*. 2017). According to FAO (2015)), acidic soils are concentrated in South America, northern and eastern North America, South-East Asia, Central and Southern Africa, northern Europe and Eurasia. About 60 per cent of the area of acidic soils is in developing countries, mainly in the tropics and subtropics. Soil acidity can be worsened by farming practices such as harvesting to

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remove grain (Lukin and Epplin 2003) and application of nitrogen fertilisers (Tian and Niu 2015).

In the cereal-producing zone of Western Australia, the wheatbelt, more than 70 per cent of topsoil has a pH lower (i.e. more acidic) than the Department of Primary Industries and Regional Development target of 5.5 for topsoil and almost half of the sub-soils have a pH lower than the target of 4.8 for sub-soil (Gazey *et al.* 2013). The impact of acidity on crop yield depends on the crop species. Fortunately for Western Australian farmers, some varieties of their main crop, wheat, are relatively acid tolerant. Even so, the value of lost production in this area due to soil acidity has been estimated at A$1.6 billion annually (Petersen 2015).

In Australia, soil acidification is commonly treated by lime application (Gazey and Gartner 2009). In Western Australia's agricultural zone, an estimated 1 million tonnes of lime per annum is currently applied, and in future, application of approximately 2.5 million tonnes of lime will be required annually to achieve soil pH targets (State of the Environment Report 2011). Liming increases soil pH (i.e. reduces acidity) and modifies the composition of the cation exchange complex. Adding lime to a highly acidic soil in the region alleviates calcium deficiency, increases nutrient availability and decreases soluble and reactive forms of aluminium, which is toxic to plants (Fornara *et al.* 2011; Viadé *et al.* 2011; Briedis *et al.* 2012). In the Western Australian wheatbelt, the potential benefits from the widespread lime application are estimated to be $A63/ha/year (Petersen 2015). Hence, lime applications can be viewed as an investment in soil productivity (Gazey *et al.* 2014b).

The benefits to farmers from applying lime are affected by biophysical and economic factors. The biophysical factors include the crop grown, soil type, initial soil acidity, nitrogen fertiliser application, rainfall and soil moisture, lime type and quality, and liming application methods (Goulding *et al.* 1989; Scott *et al.* 1992; Conyers *et al.* 1995; Kirchhof *et al.* 1995; Wang *et al.* 1999; Evans *et al.* 2001; Liu *et al.* 2004). A single application of lime takes around one year to become effective and benefits can last for over a decade (Sime 2001). Indeed, in our case-study region, soils and rainfall conditions are such that liming can generate yield benefits for 20 years or more (consistent with the time frame reported by Lukin and Epplin (2003)). Therefore, it is important to consider the carryover effects of lime from one crop season to the next.

The key economic factors affecting the economics of lime application are as follows: the price of lime at the quarry, the cost of transporting lime to the farm, the cost of spreading lime, the cost of incorporating lime into the sub-soil, the prices of grains and the farmer's personal discount rate (Edmeades *et al.* 1985; Gazey *et al.* 2014b).

Previous research on the economics of lime application has explored a range of questions, including the following: the economic losses caused by soil salinisation (Hajkowicz and Young 2005); the benefits and costs of lime application over relatively short periods, such as five years (Kaitibie *et al.* 2002), or longer periods, such as 25 years (Lukin and Epplin 2003); the benefits of variable-rate application, adjusting lime application rates to suit local conditions (Bolton *et al.* 1976; Bongiovanni and Lowenberg-DeBoer 2000; Kaitibie *et al.* 2002; Lukin and Epplin 2003; Wang *et al.* 2003; Hajkowicz and Young 2005; Calba *et al.* 2006; Mulungu *et al.* 2013).

Due to the low mobility of lime in the soil, the effect of surface application on the acidity of sub-soil horizons is slow and partial (Caires *et al.* 2005). The amendment of sub-soil acidity is particularly difficult to achieve in no-till systems due to the lack of soil disturbance (Flower and Crabtree 2011; dos Santos *et al.* 2018). No-till has become by far the most common tillage practice amongst farmers in Western Australia (Llewellyn *et al.* 2012). The incorporation of lime into sub-soil using various forms of deep tillage has shown promising results. It results in a rapid decrease in sub-soil acidity and also a reduction in soil compaction (Gazey *et al.* 2014a). However, the approach is slower and more costly than surface application.

In this study, we address the following research questions for a case study in the northern wheatbelt of Western Australia. What is the optimal rate of lime application to reduce soil acidity when the long-term dynamics of soil acidity are considered? How does the optimal rate vary depending on key contextual factors: the average rainfall for the area, and the severity and depth of acidity in the soil? What is the financial benefit to farmers from applying lime? Is deep placement of lime economically superior to surface placement, and if so, by how much? And, how sensitive are financial results to use of liming rates that deviate from the optimum? In other words, is it important to specify the lime rate precisely or is indicating a range sufficient?

To address these questions, a nonlinear dynamic optimisation model is developed that integrates a biophysical simulation model of soil acidity and wheat yield, Optlime (Sandison and Bathgate 1997; Gazey 2008) with an economic model. The model determines the comparative dynamics of the lime application rate that maximises the net present value (NPV) of income, net of the cost of lime application, for a representative continuous wheat production system for a range of acidity and rainfall conditions in Western Australia. For reasons of tractability, the frequency of lime application is set exogenously in any one model run, but is varied between model runs to test the impact on economic results.

The paper proceeds as follows. In the next section, we outline the study area and the farming system and then describe the optimisation model. Then, we present the results from the model, starting with biophysical results followed by detailed economic results. The robustness of results is investigated in a set of sensitivity analyses, and then, we summarise key conclusions from the study.

2. Method

2.1 Study area and farming system

The Western Australian wheatbelt is a 155,000 km^2 region in the south-west of Australia. Its climate is Mediterranean with cool to mild, wet winters and warm to hot, dry summers. Rainfall predominately occurs during winter (June to August) with rainfall deficits during the summer (December to February), although high-intensity thunderstorms or rain-bearing depressions associated with tropical cyclones may deliver significant rainfall in summer. Rainfall is strongly seasonal, and about 75 per cent of the annual rainfall occurs between May to October. Annual rainfall ranges from 250 mm in the north-east to 800 mm in the south-west (Burbidge *et al*. 2004; Kobayashi and Oki 2015). For this study, three zones with different rainfall patterns in the northern wheatbelt are chosen as follows: low annual average rainfall (less than 325 mm), medium annual average rainfall (325 to 450 mm) and high annual average rainfall (more than 450 mm, which is relatively high for the Western Australian wheatbelt).

The Western Australian wheatbelt is crop-dominant and produces about 14 million tonnes of grain annually. The most common crops are wheat, barley, oats, canola and lupins (Kingwell *et al.* 2003). Wheat (*Triticum aestivum* L.) accounts for the largest proportion of the cropping area in the region (Seymour *et al.* 2012). There are about 4,200 rain-fed farms ranging in size from 1000 to 15000 hectares (Wilkinson 2018). Wheat is typically sown in May and is harvested from November to December. In the study area, crop production is greatly affected by soil acidity and the resulting aluminium toxicity. The most common soil types in the area are sand and duplex (sand over clay). Due to their lower buffering capacity, sandy soils are the most susceptible soil types to acidification. However, pH recovery in these soils is quicker and less lime is required to amend acidity compared with clay soils (Fujii *et al.* 2017). This farming system is reliant on large machinery to boost labour productivity (Kingwell 2011). Reduced-tillage or no-till systems are used throughout the region to improve soil and water utilisation (Flower and Braslin 2006).

On acidic soils, lime is most commonly applied to the soil surface using a mechanical spreader. However, because lime is slow to move through the soil profile, there is growing interest in incorporating lime into the sub-soil profile. Following surface application of lime, farmers can use one of several methods for deep cultivation to band the lime into the sub-soil profile. This includes use of a mouldboard plough, a spader, a modified one-way plough or a deep ripper. These methods can incorporate lime to a depth of around 30 cm. Deep incorporation of lime typically occurs during autumn, prior to crop seeding.

2.2 Model structure

A dynamic optimisation model is developed to determine optimal lime application rates and frequency for representative crop farms in each of the three case-study zones. The model is constructed in GAMS (General Algebraic Modeling System) and solved using the CONOPT solver suitable for large-scale nonlinear optimisation. It consists of a biophysical component derived from Optlime and an economic component (see Figure 1). The model simultaneously optimises lime application rates for the surface and the subsoil profile. For reasons of tractability, the frequency of lime application is not optimised endogenously. Instead, we solve the model for several discrete frequencies and report results for two of them.

The biophysical model Optlime is fully implemented within the optimisation model (See Appendix S1 for detailed information on the model equations and parameters). Optlime has been developed, validated, used and refined in Western Australia over 20 years, based on a large number of field trials (Gazey 2008). The model predicts soil pH over time and at different soil depths in response to lime application, nitrogen fertiliser application and crop removal (Gazey 2008), depending on the level of rainfall and soil conditions. Optlime simulates crop yield as a function of soil pH and aluminium toxicity in the soil between 0 and 30 cm depth (Oliver *et al.* 2014).

The biological component integrates lime quality, lime dissolution, lime leaching, lime application methods, rainfall, soil characteristics (soil initial pH, gravel, bulk density, aluminium content and texture) and nitrogen fertiliser to determine the effect of lime application on monthly soil pH dynamics in three soil horizons: 0–10 cm, 10–20 cm and 20–30 cm. Annual

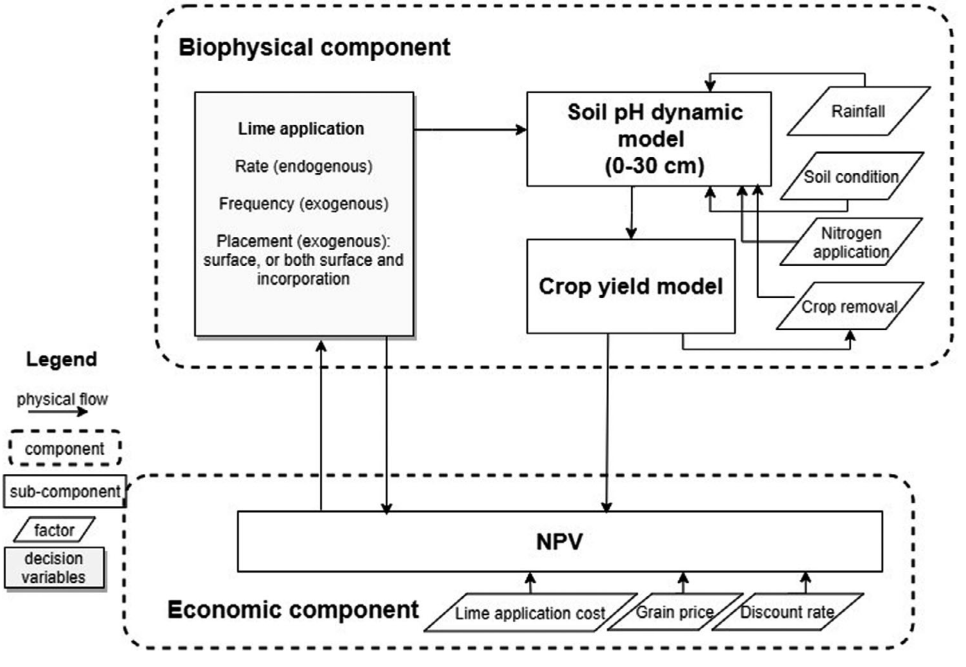

Figure 1 Structure of the dynamic optimisation model, integrating economic and biophysical components.

pH (an average of soil pH from May to October-growing season) determines annual aluminium concentration over the soil horizons and the resulting yield responses. Crop harvesting and nitrogen fertiliser application result in soil acidification that changes the annual soil pH at the end of the growing season. The simulated yield is an input into the economic component. Based on the price of grain and the costs of lime application by different methods, the economic component determines net return to the lime application given yield as a function of soil pH and aluminium toxicity in the three soil horizons.

The dynamic optimisation model combines biological and economic components to maximise NPV of a continuous wheat system over the 80-year time horizon. Most farmers have planning horizons much shorter than this, but results are shown for 80 years because of the slowness of the system to achieve equilibrium under any particular management system and the fact that any endpoint condition at the end of 80 years has a negligible effect on the solution due to discounting. It also takes a long time for the lime to disperse through the soil horizons in some soil and rainfall conditions because of the low dissolution and mobility of lime in the soil. A shorter planning horizon may result in running down the soil as it would imply that farmers do value soil health after the end of the modelling horizon. Hence, a terminal value function is added assuming that the liming, pH dynamics and yields of the last liming interval in the modelling horizon are repeated indefinitely. The approach has much in common with the Faustmann's (1968) model of forestry economics.

The problem is highly nonlinear with a large number of decision variables. It suffers from the curse of dimensionality as pH for the three different soil horizons is all state variables, and there are interactions between the soil horizons. To make the problem more tractable, it is assumed that lime is applied at fixed time intervals. We experimented with intervals of 5, 10 and 20 years and found little difference between them in terms of economic outcomes. To limit the quantity of output presented, we omit the results for a frequency of 5 years.

Although a range of crops and crop rotations are grown in the study region, the model is based on a continuous wheat production system. This assumption simplifies the model and provides a reasonable approximation of results for rotations that include other non-legume crops, such as barley, oats and canola.

2.3 Treatments

The model is solved for a range of contexts: (a) lime application frequencies of 10 and 20 years; (b) two lime-placement strategies, with lime applied to the soil surface, or both applied to the surface and incorporated into the sub-soil profile; (c) three levels of average rainfall (<325 mm, 325–450 mm and > 450 mm per year); (d) three soil-acidity conditions, with acidity in the soil surface layer, or in the sub-soil profile, or both. In the modelling scenarios, 'acidic' soil means initial soil pH levels of 4.6 for the 0-10 cm of soil horizon, 3.8 for the 10-20 cm horizon and 4.1 for 20–30 cm. Non-acidic soil horizons are assumed initially to have pHs of 5.8, 5.8 and 6.5, respectively. (See initial soil pH, pH_i^0, of different acidic soil layers in Table S1 of Supplementary Material). A soil with an acidic topsoil is not necessarily acidic in the sub-soil profile.

3. Result and discussion

3.1 Soil-acidity and yield responses to lime

The yield and soil-acidity responses to optimal lime decisions vary with rainfall, the severity of soil-acidity conditions and liming frequency and methods. Figure 2 shows results for the 325–450 mm rainfall zone, for the three liming strategies (zero lime and two lime-placement strategies), under three soil-acidity conditions, and for liming every 10 years. The results shown are from the dynamic optimisation model – lime rates are optimal (i.e. they maximise NPV) for the conditions modelled, except in those scenarios that are constrained to include no lime application.) Based on the parameters and functions of Optlime, the wheat yield is more sensitive to sub-soil acidity than to topsoil acidity.

Graphs (a), (d) and (g) are for no lime application. In the graph (a), the crop yield initially remains high despite the acidic topsoil but starts to fall once sub-soils reach high levels of acidity, below pH 4.1 in $CaCl_2$. Wheat is moderately tolerant of soil acidity but below this pH level wheat production in this region is significantly affected due to aluminium concentration in the

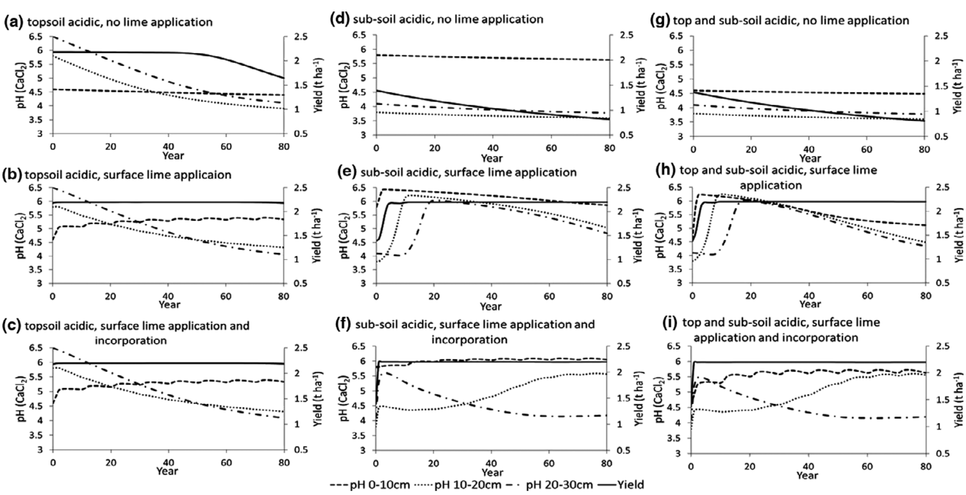

Figure 2 Responses of yield and pH at the end of growing season to liming options (every 10 years) for 325-450mm rainfall zone with different soil-acidity conditions.

soil being raised to toxic levels (Gazey 2008). In graphs d and g, where sub-soils are initially acidic, yields start low and continue to decline slowly, even if the topsoil is not acidic (graph d).

Graphs (b), (e) and (h) are for the scenarios where lime is applied to the surface only. In the case of topsoil acidity only (graph (b)), relatively low rates of lime in year 1 and every 10 years ameliorate the topsoil acidity and maintain high yields throughout the period. The optimal lime rates are given in Table 1. Where the sub-soil is acidic but only surface application of lime is allowed (graphs e and h), it is optimal to apply a very high initial lime rate to the soil surface (Table 1). This improves sub-soil acidity sufficiently to improve crop yields within three years, although sub-soil acidity continues to improve for around 15-20 years. In the absence of a further lime application, soil acidity worsens after that (i.e. pH falls), but not enough to reduce crop yields within 80 years.

The bottom row of graphs ((c), (f) and (i)) are the scenarios where lime can be applied to the surface, incorporated into the sub-soil profile or both. The first result (c), where there is only topsoil acidity, includes only surface lime application, and so it is identical to result (b). In the result (f), where there is only sub-soil acidity, and the result (i), where all three soil layers are acidic, it is optimal to both apply lime to the soil surface and incorporate it into the sub-soil profile. Acidity in the second soil layer (10-20 cm) reduces rapidly. In the third layer, it takes longer to recover. In both cases, the crop yield increases within one year and stays high throughout the period.

3.2 Optimal liming strategies

Table 1 shows the optimal liming strategies for six of the nine scenarios presented in Figure 2 (excluding results for no liming). Figure 2 is based on annual rainfall of 325-450 mm per year, but Table 1 includes results for the low-, medium- and high-rainfall zones. In broad terms, in all three rainfall zones, optimal lime usage is lowest where only the topsoil is acidic, highest where the sub-soil is acidic but only surface application is used, and intermediate where both surface and incorporated lime application are used. When the sub-soil is acidic, it is optimal to apply high rates of lime to the soil surface, or else to invest in the more expensive incorporation of lime into the soil. When lime is incorporated into the sub-soil profile, the total amount of lime applied in year one is reduced from 8–10 tonnes per hectare to 3–4 tonnes per hectare. This is because there is a limited and delayed capacity of surface liming to address sub-soil acidity, which is partly replaced by lime incorporation.

The effect of rainfall on optimal liming practices is complex. First, where the surface application of lime is used to treat sub-soil acidity, optimal surface application rates are lower at higher rainfall levels as a result of higher rainfall helping to transport lime through the soil profile. Second, optimal surface rates, in particular, maintenance rates, are greater at higher rainfall levels

Table 1 Optimal lime application rates (t/ha) with 10-year liming frequency for different rainfall, acidity conditions and liming options

Annual rainfall (mm)	Acidity condition	Liming option	Lime application rate (t/ha)		
			Surface (year 1)	Incorporated (year 1)†	Surface maintenance (every 10 years)
<325	Topsoil	Surface	0.6	–	–
		Surface and incorporation	0.6	–	–
	Sub-soil	Surface	10.1	–	–
		Surface and incorporation	0.1	3.2	0.1
	Top and sub-soil	Surface	8.6	–	–
		Surface and incorporation	0.8	3.0	0.1
325-450	Topsoil	Surface	0.6	–	0.2
		Surface and incorporation	0.6	–	0.2
	Sub-soil	Surface	9.6	–	–
		Surface and incorporation	0.2	3.2	0.5
	Top and sub-soil	Surface	8.1	–	–
		Surface and incorporation	0.9	2.8	0.5
>450	Topsoil	Surface	0.6	–	0.7
		Surface and incorporation	0.6	–	0.7
	Sub-soil	Surface	9.4	–	0.1
		Surface and incorporation	0.6	3.2	0.9
	Top and sub-soil	Surface	7.8	–	0.5
		Surface and incorporation	1.4	2.8	0.9

Note: †Optimal lime application rate is split equally between the two sub-soil layers 10–20 cm and 20–30 cm.

where lime is incorporated into the acidic sub-soil layer. This increase is related to higher nitrogen leaching and consequently higher acidification rates in the subsequent years. This trend is more apparent when surface and incorporated lime application is used to amend both top and sub-soil acidity. Across all rainfall levels, optimal lime rates are lower when there is both top- and sub-soil-acidity condition compared to the scenario with only sub-soil acidity. This perhaps-surprising result (lower rates when more of the soil profile is acidic) is explained by the fact that surface-applied lime is more soluble when the topsoil is more acidic, facilitating greater transfer of alkalinity to lower soil horizon.

Most of the optimal lime application rates are influenced only slightly by changing lime application frequency from every 10 years to every 20 years. All of the optimal application rates for year 1 are the same or only slightly increased when the frequency is reduced (Tables 1 and 2). However,

Table 2 Optimal lime application rates (t/ha) with 20-year liming frequency for different rainfall, acidity conditions and liming options

Annual rainfall (mm)	Acidity condition	Liming option	Lime application rate (t/ha)		
			Surface (year 1)	incorporated (year 1)†	Surface maintenance (every 20 years)
<325	Topsoil	Surface	0.6	–	–
		Surface and incorporation	0.6	–	–
	Sub-soil	Surface	10.1	–	–
		Surface and incorporation	0.2	3.2	0.2
	Top and sub-soil	Surface	8.6	–	–
		Surface and incorporation	0.9	3.0	0.2
325-450	Topsoil	Surface	0.7	–	0.4
		Surface and incorporation	0.7	–	0.4
	Sub-soil	Surface	9.6	–	0.0
		Surface and incorporation	0.5	3.0	1.0
	Top and sub-soil	Surface	8.1	–	–
		Surface and incorporation	1.2	2.8	1.0
>450	Topsoil	Surface	0.8	–	1.6
		Surface and incorporation	0.8	–	1.6
	Sub-soil	Surface	9.4	–	0.3
		Surface and incorporation	0.9	3.0	2.1
	Top and sub-soil	Surface	7.8	–	1.0
		Surface and incorporation	1.6	2.8	2.1

Note: †Optimal lime application rate is split equally between the two sub-soil horizons 10–20 cm and 20–30 cm.

increases in optimal maintenance rates are larger, approximately doubling in all cases.

3.3 NPV responses

Table 3 shows NPVs for each scenario, for both the 10- and 20-year lime application frequencies. Sub-soil acidity has a larger impact on profits than does topsoil acidity. This is especially true if no lime is applied, but remains true even if lime is applied. Across all rainfall levels, surface lime application is optimal to ameliorate topsoil acidity and surface plus incorporated lime application is the optimal liming option to amend sub-soil acidity. Increases in rainfall level improve profits in all acidity conditions. However, changes in liming frequency have almost no effect on profits.

Table 3 NPV ($ per ha) and extra benefit for surface and incorporated lime application relative to surface liming (per cent) for different rainfall, acidity conditions, liming options and frequency

Annual rainfall (mm)	Acidity condition	Liming option	NPV ($ per ha)		Extra benefit (per cent)	
			Frequency 10	Frequency 20	Frequency 10	Frequency 20
<325	Topsoil	No lime	8,589	8,589	–	–
		Surface	8,648	8,648		
		Surface and incorporation	8,648	8,648		
	Sub-soil	No lime	5,113	5,113	7.0	7.0
		Surface	7,934	7,934		
		Surface and incorporation	8,486	8,486		
	Top and sub-soil	No lime	5,068	5,068	4.3	4.3
		Surface	8,122	8,122		
		Surface and incorporation	8,467	8,467		
325-450	Topsoil	No lime	10,377	10,377	–	–
		Surface	10,569	10,569		
		Surface and incorporation	10,569	10,569		
	Sub-soil	No lime	5,786	5,786	4.4	4.4
		Surface	9,955	9,955		
		Surface and incorporation	10,394	10,394		
	Top and sub-soil	No lime	5,735	5,735	2.7	2.7
		Surface	10,106	10,106		
		Surface and incorporation	10,377	10,377		
>450	Topsoil	No lime	12,597	12,597	–	–
		Surface	13,436	13,437		
		Surface and incorporation	13,436	13,437		
	Sub-soil	No lime	6,827	6,827	2.8	2.7
		Surface	12,895	12,897		
		Surface and incorporation	13,255	13,252		
	Top and sub-soil	No lime	6,766	6,766	1.7	1.6
		Surface	13,018	13,024		
		Surface and incorporation	13,239	13,238		

Table 4 shows that applying lime is substantially more profitable than not applying it. Surface lime application, relative to no lime application, increases profit by 1-7 per cent in topsoil-acidity conditions and by 55-92 per cent in sub-soil-acidity conditions, depending on rainfall levels. If there is sub-soil acidity, the best solution is to combine surface and incorporated lime application. This results in up to 96 per cent increase in NPV compared with no lime application. Compared to the strategy that only applies lime to the soil surface, the additional benefit of also incorporating lime into the sub-soil is small – 5 per cent or less in most cases (Table 4). In other words, compared

Table 4 The ratio of NPV with and without lime application for different rainfall, acidity conditions and liming options (every 10 years)

Annual rainfall (mm)	Acidity condition	Liming option	Ratio of NPV
<325	Topsoil	No lime	1
		Surface	1.01
		Surface and incorporation	1.01
	Sub-soil	No lime	1
		Surface	1.55
		Surface and incorporation	1.60
	Top and sub-soil	No lime	1
		Surface	1.60
		Surface and incorporation	1.67
325–450	Topsoil	No lime	1
		Surface	1.02
		Surface and incorporation	1.02
	Sub-soil	No lime	1
		Surface	1.72
		Surface and incorporation	1.80
	Top and sub-soil	No lime	1
		Surface	1.76
		Surface and incorporation	1.81
>450	Topsoil	No lime	1
		Surface	1.07
		Surface and incorporation	1.07
	Sub-soil	No lime	1
		Surface	1.89
		Surface and incorporation	1.94
	Top and sub-soil	No lime	1
		Surface	1.92
		Surface and incorporation	1.96

with surface application, the additional costs of incorporating lime almost cancel out the additional benefits.

3.4 Sensitivity analysis

Due to the uncertainty involved in the estimation and specification of key parameters within the model, the sensitivity of the key results (optimal lime application rates and the NPV) to alternative values of the selected parameters is examined. We test the sensitivity of results to changes in initial soil pH, wheat and lime prices, the distance of the farm from the lime quarry, and discount rate.

All sensitivity analyses presented are for the 325–450 mm rainfall zone under 10-year application frequency. They are all for surface liming as it is the most common liming method in the study area.

3.5 Initial soil pH

Optimal lime rates in the base model are extremely sensitive to changes in initial pH (Table 5). The first row of results is for high acidity in all three soil

Table 5 Optimal lime application rate (t/ha) and NPV ($ per ha) responses to alternative values of initial soil pH ($CaCl_2$) in the 325–450 mm rainfall zone under surface liming (every 10 years)

Initial pH ($CaCl_2$)			Lime application rate (t/ha)		NPV ($ per ha)
0–10 cm	10–20 cm	20–30 cm	Surface (year 1)	Surface maintenance (every 10 years)	
4.6	3.8	4.1	8.1	–	10,106
4.8	4.0	4.3	4.0	–	10,415
5.0	4.2	4.5	1.8	0.4	10,521
5.2	4.4	4.7	0.7	0.7	10,548
5.4	4.6	4.9	0.1	0.7	10,563
5.6	4.8	5.1	–	0.6	10,572

horizons. In subsequent rows, the pH of each soil horizons is increased simultaneously in steps of 0.2. The first step increase in pH results in a large reduction in the optimal surface rate in year one but no change in surface maintenance rates (every 10 years). Further increases in pH gradually decrease the optimal surface rate in year one and increase the optimal surface maintenance rate in the following years. This switch from up-front applications to maintenance applications reflects that, at higher initial pHs, the relative impact of soil acidity is higher in the future, rather than the present.

The first step change in acidity has a relatively large impact on NPV, but after the second step, the benefit of additional decreases in acidity is very small. These results reinforce the importance of initial soil-acidity condition as one of the key parameters in determining the optimal decision rules for lime application.

3.6 Wheat and lime prices

Lime rates are highly sensitive to wheat prices but much less sensitive to lime prices. The effects of $\pm$ 30 percentage change in both wheat and lime prices on optimal lime rates and NPV responses are shown in Table 6. Across these conditions, the optimal initial lime rate varies from 6.6 to 9.6 t/ha. Results are more sensitive to wheat price than to lime price because revenue is proportional to wheat price but lime constitutes a relatively small proportion of production costs.

3.7 Distance from the lime quarry and discount rate

Optimal surface lime application rate in year one is sensitive to distance from lime quarry, which affects the overall cost of lime application, but less sensitive to discount rate (Table 7). For instance, every 100 km increase in the distance from lime quarry decreases the initial surface lime rate by around one tonne per hectare without increasing the subsequent maintenance rates which are zero. NPV is not very sensitive to distance from lime quarry compared with discount rate. Changing the discount rate from 5 to 10 per cent decreases the NPV by $5,270 per hectare.

3.8 Bound on lime rate

When there is sub-soil acidity but lime is only applied at the surface, optimal rates are much higher than those actually applied by farmers in the study region. For example, optimal surface liming rates in year one, when topsoil and sub-soil profiles are acidic, are 8-10 t/ha. It is interesting to explore results where lime rates are constrained to lower, sub-optimal levels, more in line with current farming practices. Table 8 shows that, for both lime application frequencies of 10 and 20 years, substantial reductions in initial lime rate are possible with minimal impacts on profit. For example, reductions in optimal

Table 6 Optimal lime application rate (t/ha) for ± 30 percentage change in both wheat and lime prices in the 325-450 mm rainfall zone with top and sub-soil acidity under surface liming (every 10 years)

Wheat price (percentage change)	Lime price (percentage change)		
	−30	Base case	+30
Surface lime rate (year 1) (t/ha)			
−30	7.2	6.9	6.6
Base case	8.5	8.1	7.7
+30	9.6	9.2	8.7
NPV ($ per ha)			
−30	7,031	7,011	6,992
Base case	10,130	10,106	10,084
+30	13,239	13,212	13,186

Table 7 Optimal lime application rate (t/ha) and NPV ($ per ha) responses to alternative values of distance from lime quarry (km) and discount rate in the 325-450 mm rainfall zone with top and sub-soil acidity under surface liming (every 10 years)

Parameters	Lime application rate (t/ha)		NPV ($ per ha)
	Surface rate (year 1)	Surface maintenance (every 10 years)	
Base case: Distance from lime quarry (100 km) and Discount rate (5 per cent real)	8.1	–	10,106
Distance from lime quarry (200 km)	7.1	–	10,035
Distance from lime quarry (300 km)	6.4	–	9,971
Discount rate (10 per cent real)	7.7	–	4,836

Table 8 Percentage change in NPV for sub-optimal lime rates (t/ha), relative to optimal rates, in the 325-450 mm rainfall zone for different acidity conditions and surface liming frequency

Acidity condition						
Sub-optimal lime rate (t/ha)	Topsoil		Sub-soil		Top and sub-soil	
	Frequency 10	Frequency 20	Frequency 10	Frequency 20	Frequency 10	Frequency 20
2	–	–	−7	−9	−8	−11
3	–	–	−4	−4	−4	−4
4	–	–	−2	−2	−2	−2
5	–	–	−1.2	−1.2	−0.7	−0.7
6	–	–	−0.6	−0.6	−0.2	−0.2

lime rates from 8-10 t/ha to sub-optimal lime rate of 4 t/ha reduce NPV by only 2 per cent. This is consistent with the common observation that payoff curves for agricultural inputs are often flat for wide ranges around their maxima (Pannell 2006). The fact that farmers in the study region apply less than optimal rates of lime is of little economic importance.

Liming is important in soil-acidity management and has major impacts on crop production (Holland *et al.* 2018). Liming at a broadly appropriate rate is much more profitable than not liming, although the specific rate, application method or frequency does not affect NPV greatly. Lime application is a long-term investment, which might make it less attractive to farmers with short planning horizons, such as farmers with limited finances, leased land or share farms.

Overall, the sensitivity analysis shows that the optimal liming strategy is most sensitive to the initial soil-acidity conditions. The other factors studied have some influence, but do not radically alter the results, with wheat price having the second largest effect. Notably, profit is not sensitive to moderate reductions in lime application rate below the optimal rate.

4. Conclusion

A dynamic optimisation model has been used to explore optimal lime application strategies to manage soil acidity over different soil horizons in different rainfall zones of the wheatbelt in Western Australia. Results indicate that soil acidity can be remediated by applying lime at appropriate rates and that the economic benefits of this strategy clearly outweigh the costs. Combining surface and incorporated lime application methods results in a slightly higher NPV compared with the surface-only application, but probably not by enough to make incorporated lime application a compelling option for most farmers. Higher lime rates are required to amend soil acidity in high-rainfall zones, particularly with the sub-soil is highly acidic. Varying the frequency of lime application makes little difference to the long-term NPV, although it slightly affects optimal lime application rates.

Although optimal lime application rates are substantially higher than rates typically used by farmers in the case-study region, sensitivity analysis reveals that lower rates, more in line with current farming practices, are only slightly less profitable than the optimal rates.

This study has a number of limitations. In this study, liming has been looked at solely as a private investment, with all of the benefits captured by the farmers who apply the lime and the suppliers of lime. Management of acidity could have some public-good implications, such as greenhouse-gas emissions, that have not been represented in this paper. Shoghi Kalkhoran et al. (2019) analyse the economic interaction between liming and climate-change policy.

A key factor influencing soil acidification is application of nitrogen fertiliser. The consideration of nitrogen also relates to the inclusion of a legume crop in the rotation. These issues are not explored in this study but are addressed by Shoghi Kalkhoran et al. (2020).

The impact of year-to-year climatic variability on the management decisions was not considered. Given the long-time frames over which strategies for alleviating soil acidity play out, it seems likely that season-to-season variation in weather would not greatly affect the economic results for liming, relative to a model based on average climate.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Supplementary Material for detailed information on the dynamic optimization model equations and parameters.