A Dynamic Model of Optimal Lime Applications for Wheat Production in Australia

Sanaz Shoghi Kalkhoran[a*], **David J. Pannell**[a], **Benedict White**[a], **Maksym Polyakov**[a], **Morteza Chalak**[a], **Amin Mugera**[a] **and Imma Farre**[b]

[a] UWA, School of Agriculture and Environment

[b] Department of Agriculture and Food WA

[*] Email: sanaz.shoghikalkhoran@research.uwa.edu.au

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Abstract

Soil acidification due to crop removal and the use of acidifying fertilizers reduces land productivity across agricultural systems worldwide. The standard remedy is to periodically apply lime to the soil surface which, over a number of years, is assimilated into the soil profile and raises soil pH. However, an alternative approach is to incorporate lime into the sub-soil. This is more expansive, but substantially reduces the time required to reduce acidity deeper in the soil profile. This paper presents a dynamic model to determine an optimal timing, levels, and methods of lime application for a cereal crop. Using the Western Australian Wheatbelt as a case study region and wheat as the cereal crop, results show how optimal application rate and frequency vary between regions with different levels of rainfall and between soils with different initial soil pH. Incorporating lime through the soil increases net present value by up to 7% compared to traditional surface lime applications, reduces optimal lime application rates and reduces the time required for soil acidity amendment.

Keywords

Dynamic optimization; economics; lime application; soil acidity; wheat

1 Introduction

Acidification of soils is mostly due to crop harvesting that removes base cations such as calcium, magnesium, potassium and sodium in the grain (Lukin and Epplin, 2003) and the application of nitrogen fertilizers that increases hydrogen ions in the soil (Tian and Niu, 2015). About 50% of arable lands worldwide are acidic (Li et al., 2017; Zheng, 2010). According to FAO (2015), acidic soils are concentrated in South America, northern and eastern North America, South-East Asia, Central and South Africa; and northern Europe and Eurasia. About 60% of the area of acidic soils is in developing countries, mainly in the tropics and subtropics.

In the agricultural zone of Western Australia (WA), more than 70% of top soils have a pH lower (i.e., more acidic) than the Department of Agriculture Western Australia (DAFWA) target of 5.5 and almost half of the subsoils have a pH lower than DAFWA's target of 4.8 (Gazey et al., 2013). The value of lost production in this area due to acidity has been estimated at \$A1.6 billion year^{-1} (Williams, 2016). Liming increases the yield of wheat, the most significant crop in the WA agricultural zone, the potential benefits from widespread lime application estimated at \$A63 ha^{-1}year^{-1} (Williams, 2016). In WA's agricultural zone, an estimated 1 million tonnes of lime per annum is currently applied. In the next ten years, application of approximately 2.5 million tonnes of lime will be required annually to achieve soil pH targets in this area (State of the Environment Report, 2011).

In Australia, acidification is commonly treated by applications of the minerals lime-sand, coastal limestone and dolomite (Gazey and Gartner, 2009). Liming increases soil pH and modifies the composition of the cation exchange complex. These changes can decrease soluble and reactive forms of aluminium (which otherwise can reach toxic concentrations in many Australian soils), alleviate calcium deficiency, reduce positive charged ions in the soil, and increase nutrient availability (Briedis et al., 2012; Fornara et al., 2011; Viadé et al., 2011). Lime applications can be viewed as an investment in soil productivity (Gazey et al., 2014b).

The decision to apply lime is affected by biophysical and socio-economic factors. Biological factors are the crop grown, soil type, initial pH, nitrogen fertiliser applications, rainfall and soil moisture, lime type and quality, and liming methods

(Conyers et al., 1995; Evans et al., 2001; Goulding et al., 1989; Kirchhof et al., 1995; Liu et al., 2004; Scott et al., 1992; Wang et al., 1999). A single application of lime takes almost one year to achieve maximum effectiveness, and benefits can last six years or more (Sime, 2001). Therefore, it is important to consider the carryover effects of lime from one crop season to the next; the optimal application rate and timing of lime application should account for the residual benefit of lime. By considering lime costs pay back over a 5 year period, surveys such as those conducted by Kaitibie et al. (2002) in the southern plains of Oklahoma suggest that risk-neutral or risk-averse farmers should apply lime before the initial growing season. In Zambia, Mulungu et al. (2013) showed that plots to which lime were applied at rates lower than optimal still had higher yields than un-limed plots and were profitable due to high marginal rates of return, suggesting that increasing the uptake of lime and, thus, increasing smallholder farmer yields and income. Similarly, the study of lime application in Indiana evaluated the profitability of variable rate application for lime as a stand-alone activity. The researchers concluded that the annual returns to crop production increased with site-specific pH management strategies (Bongiovanni and Lowenberg-DeBoer, 2000).

The key economic factors affecting the economics of lime application are: purchase cost 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).

To investigate optimal surface and sub-surface lime application rates, liming frequency and potential economic returns to different liming methods, we develop a dynamic optimization model that integrates a biophysical model of soil pH and wheat yield with an economic model. It is based on the Optlime simulation model (Gazey, 2008;

Sandison and Bathgate, 1997). The model determines the pattern of lime application (rate and frequency) that maximises the Net Present Value of farm net income for a continuous wheat production system.

Our study makes two contributions to the literature. Many previous studies estimated optimal static levels of lime application (Bolton et al., 1976; Bongiovanni and Lowenberg-DeBoer, 2000; Calba et al., 2006; Hajkowicz and Young, 2005; Kaitibie et al., 2002; Lukin and Epplin, 2003; Mulungu et al., 2013; Wang et al., 2003). There have been a small number of modelling studies that estimated soil pH change over time by considering the carryover effect of lime e.g., Lukin and Epplin (2003) although they ignored the effects of rainfall and the depth to which lime is incorporated. This study is the first to model the dynamic effects of lime on pH for a range of soil horizons and to determine optimal rates of lime applications accounting for those dynamic effects.

The second contribution is to investigate the economics of deep placement of lime to more effectively treat sub-surface soil acidity. Surface application is the most common method. It involves lime distribution on the surface without incorporation; however, due to the low mobility of lime in the soil, surface lime application does not reduce the acidity of sub-surface soil horizons in the short term (Caires et al., 2005). The amendment of subsoil acidity is particularly difficult to achieve in no-till systems due to the lack of soil disturbance (dos Santos et al., 2018; Flower and Crabtree, 2011). No-till has become by far the most common tillage practice amongst farmers in Western Australia (Llewellyn et al., 2012). The deep placement of lime into sub-surface by direct injection during deep ripping has shown promising results with a rapid decrease in sub-surface soil acidity, in particular where compaction is also a soil constraint

(Gazey et al., 2014a). In this technique, lime is injected into the sub-soil using a slitter blade attached to a diesel (Anderson and Hendrick, 1983). However, high costs and slow operation of the required machinery and poor distribution of lime are the potential risks of this method (Davies et al., 2015; Gazey et al., 2014a; Osman, 2013). We also aim to compare the economic benefits of different lime application methods in terms of addressing both top and sub-soil acidity.

2 Methods

2.1 Study area and farming system

The WA Wheatbelt is a 155,000 km^2 region in the south-west of Australia. The climate is Mediterranean with cool to mild, wet winters and warm to hot, dry summers. Rainfall predominately occurs over winter with rainfall deficits over the summer, although high-intensity thunderstorms or rain-bearing depressions associated with tropical cyclones may deliver significant rainfall over summer. Rainfall is strongly seasonal and about 75% of 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 were chosen: 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) (See Figure 1).

WA produces about 14 million tonnes of grain annually. Farming system in this region is crop-dominant. The most common crops are wheat, barley, oats, canola and lupins (Kingwell et al., 2003). Wheat (Triticum aestivum L.) is the largest cereal crop in Australia and this particularly the case in WA Wheatbelt (Seymour et al., 2012). It is produced in this region on about 4200 rain-fed farms ranging in size from 1000 to

15000 hectares (Wilkinson, 2018). Wheat is typically sown in May and is harvested in about November-December. Crop production in the region is greatly affected by soil acidity and the main cause of yield decline at low pH in this region is aluminium toxicity. The most common soil types in the area are sand and duplex (sand over clay). Sandy soils are the least-tolerant soil types to acidification due to their lower buffering capacity. However, pH recovery in these soils is quicker and less lime is required to amend acidity compared to clay soils (Fujii et al., 2017). Farming system of the region is reliant on large machinery that can boost labour productivity (Kingwell, 2011). Reduced-tillage or no-till systems are used throughout the region.

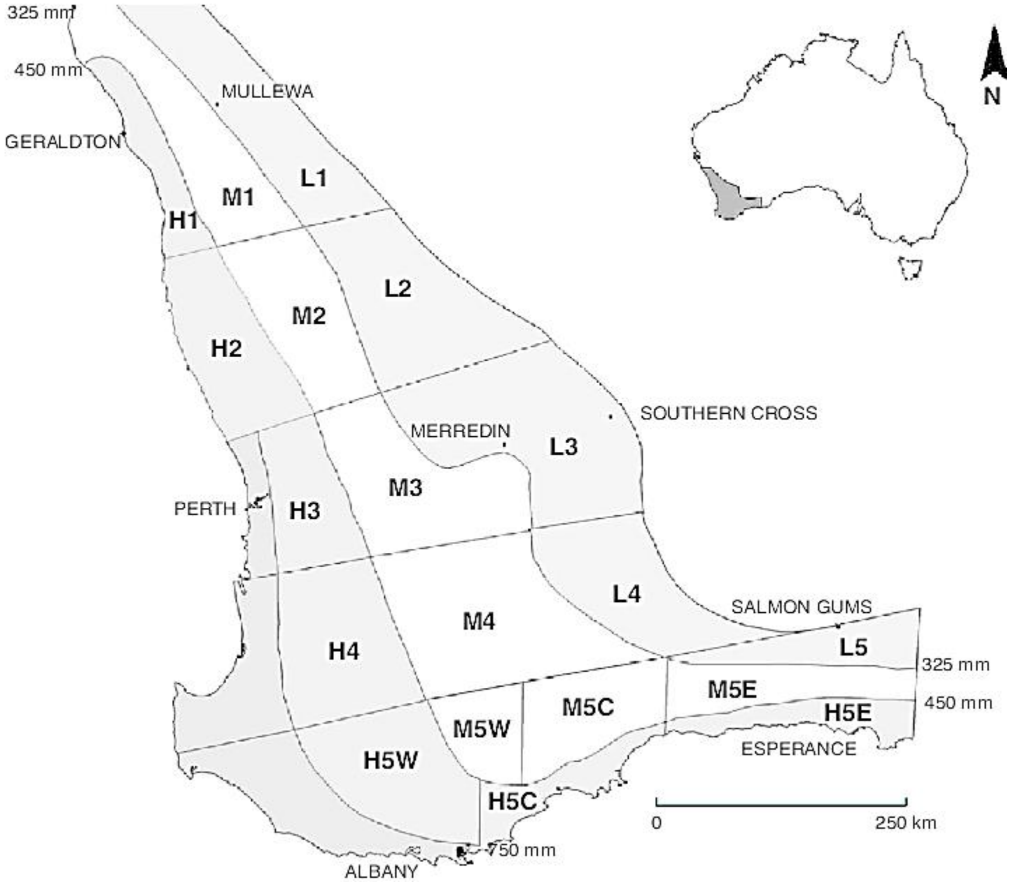

Figure 1. WA Wheatbelt region showing case-study zones H1, M1 and L1 with average annual rainfall >450mm, 325-450mm and <325mm rainfall patterns (Owen et al., 2007)

2.2 Model structure

We develop a dynamic optimization model to determine optimal lime application rates and frequency for representative crop farmers in each of the case-study zones. The model was constructed in GAMS (General Algebraic Modeling System) using the CONOPT solver and consists of a biophysical model derived from Optlime and an economic model (see Figure 2). Optlime is a simulation model that predicts soil pH responses to lime application, nitrogen fertiliser application and crop removal (Gazey, 2008). Optlime simulates crop yield as a function of soil pH and aluminium toxicity in the soil between 0-30cm depth (Oliver et al., 2014). The biological model integrates soil characteristics (soil initial pH, gravel, bulk density, aluminium and texture), rainfall, nitrogen fertilizer, lime quality, lime dissolution, lime leaching and lime application methods to determine the effect of lime application on monthly soil pH dynamics in three different layers of soil horizon (0-10cm, 10-20cm and 20-30cm). Annual 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 harvest and nitrogen application result in soil acidification that changes soil pH at the end of growing season yearly. The simulated yield is fed into the economic model. The economic model determines net return to lime application given yield as a function of soil pH and aluminium toxicity over the three soil horizons considering the price of crop and the costs of lime application by different methods. The dynamic optimization model combines biological and economic models to maximise net present value (NPV) of a continuous wheat system over a long time horizon. The model state variables are soil pH in three soil horizons, 0-10cm, 10-20cm and 20-30cm. The decision variables are lime application rates and frequency for surface and sub-surface applications (Detailed information on the model equations and parameters is available upon request from the first author). To improve the tractability of solving the model, it is constrained to apply lime at regular intervals. In different model runs, the intervals are set at 10 or 20 years.

Continuous wheat production is not commonly practiced in the study region. However, continuous cropping is practiced by many farmers, including a range of crop types, and our model approximates these crop-rotation systems.

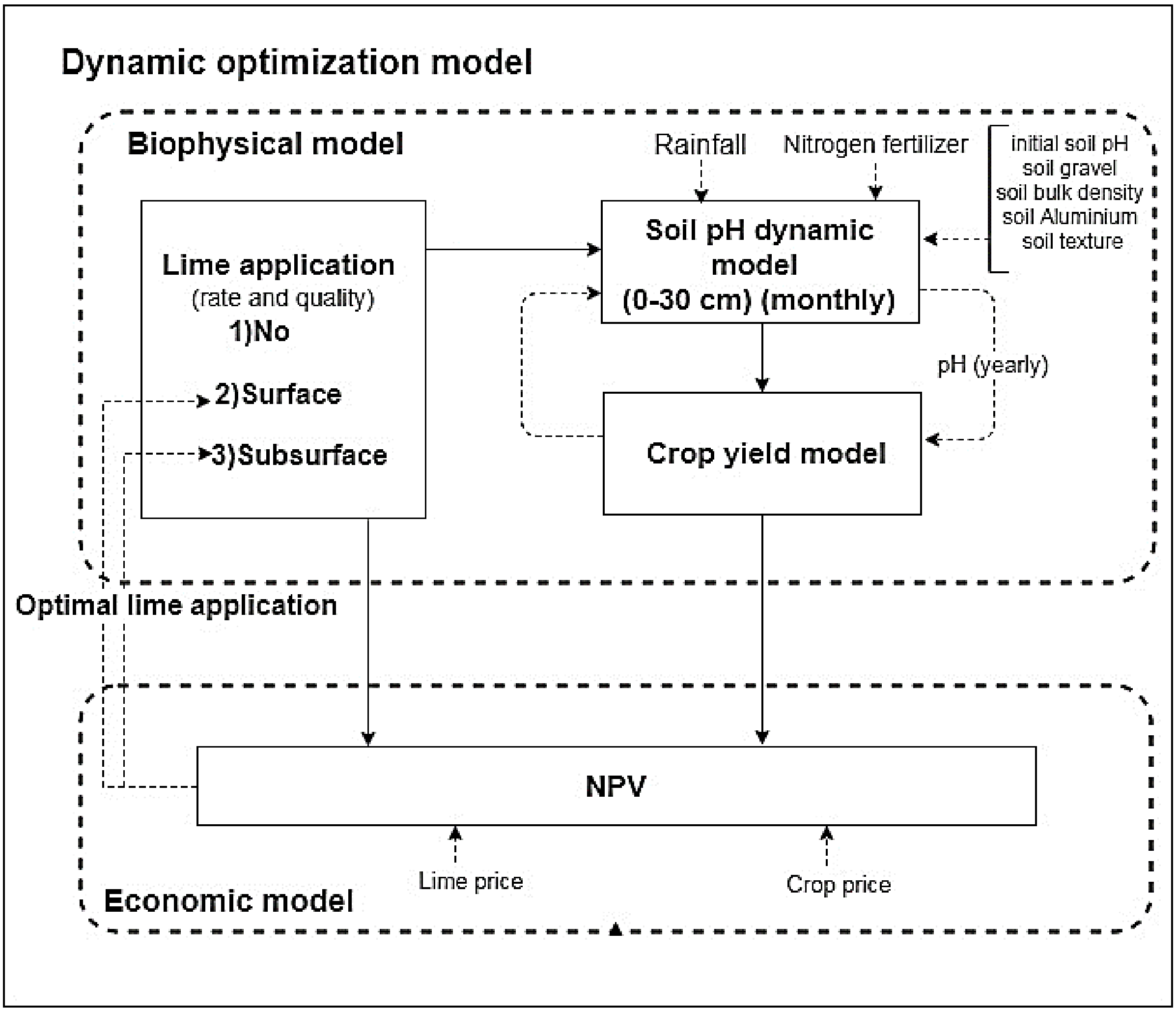

Figure 2. Model structure

2.3 Treatments

To examine the impact of rainfall, soil acidity severity and liming methods on optimal lime rate and frequency in the wheat cropping system, a combination of three acidic soil layers (top, sub and both), three rainfall levels (<325 mm, 325-450 mm and >450 mm) and two lime application options (surface and surface plus subsurface) were assessed. 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 to have pHs of 5.8, 5.8 and 6.5, respectively. A soil with an acidic surface layer is not necessarily acidic in the sub-soil layers.

3 Results and discussion

3.1 Base model output

3.1.1 Soil acidity and yields

The yield and soil pH responses to optimal lime decisions under different treatments vary broadly with rainfall, severity of soil acidity conditions and liming options. Figure 3 shows results for the 325-450mm rainfall zone, for three broad liming strategies under three acidity conditions, and for a 10-year frequency of liming. The results shown are from the dynamic optimisation model – lime rates are optimal (maximum NPV) for the conditions modelled (apart from scenarios which preclude lime application). Results are shown over an 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 equilibrate under any particular management system.

The top three graphs (a, d and g) are for no lime application. Looking at graph a), crop yield remains high despite the acidic surface soil, but starts to fall once sub-soils reach high levels of acidity, below pH 4.1 in $CaCl_2$. This pH is identified as a critical level for wheat production based on wheat being moderately tolerant of soil acidity (Gazey, 2008). This highlights the importance of sub-soil pH as an influence on yield, mainly because, in soils in this region, high acidity increases the concentration of aluminium to levels that are toxic to plants. In graphs d) and g), where sub-soils are acidic from the start, yields start low, and continue to decline slowly. This is true even if the surface soil is not acidic (graph d). Based on the parameters and functions of Optlime, wheat yield is more sensitive to sub-surface acidity than to surface acidity.

The central row of graphs (b, e and h) are for scenarios where lime is applied to the surface only. In the case of surface acidity only (graph b), low rates of lime up front and every 10 years ameliorate the surface acidity, and maintain high yields throughout the period. (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. This improves sub-surface acidity sufficiently to improve crop yields within three years, although deep acidity continues to improve for around 15-20 years. In the absence of further lime application, pH declines thereafter, but not enough to reduce crop yields within 80 years.

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

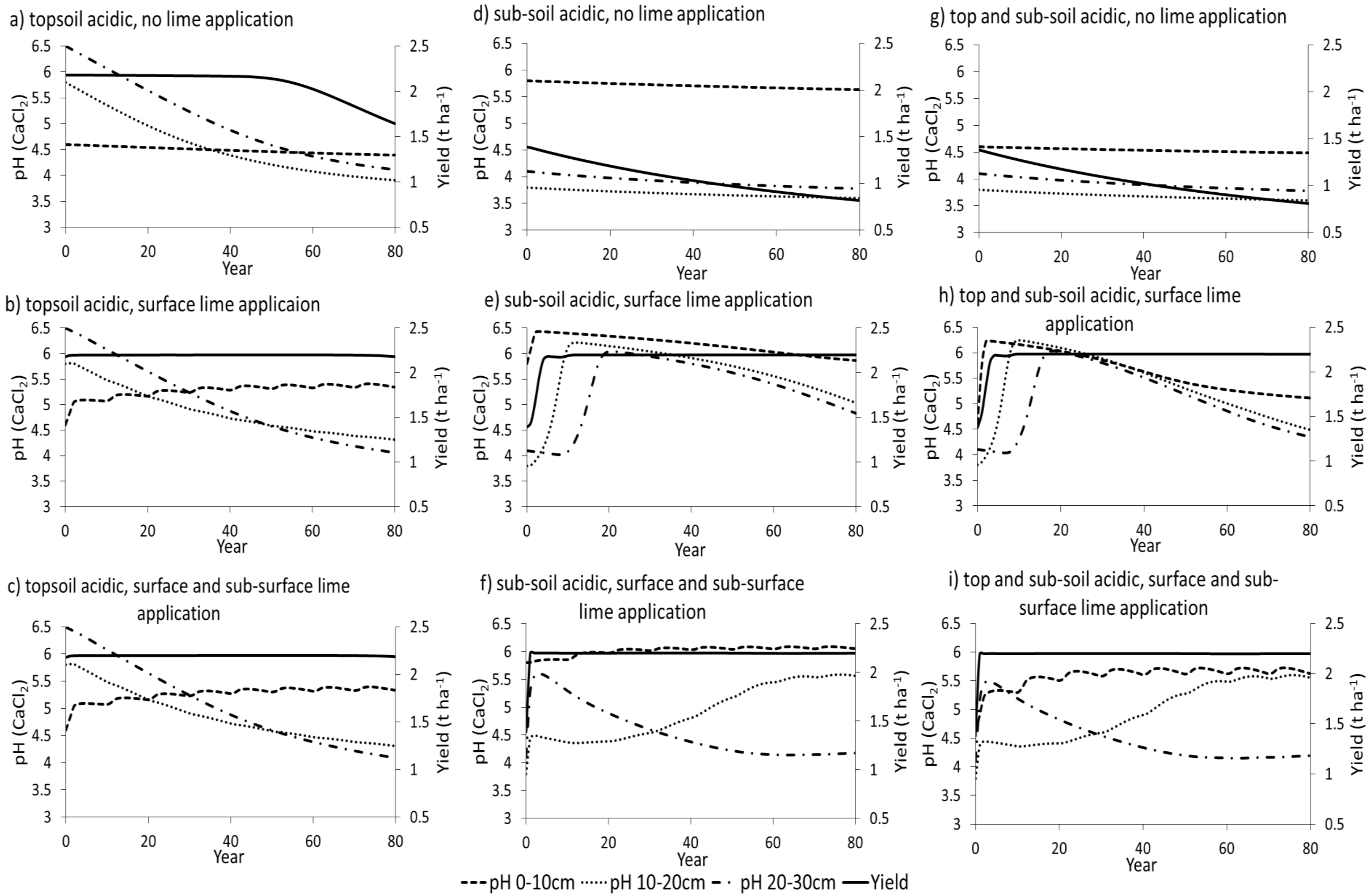

Figure 3. Yield and pH at the end of growing season response to liming options (10 yearly) for 325-450mm rainfall region with different soil acidity condition

3.1.2 Optimal liming strategies

Table 1 shows the optimal liming strategies for six of the nine scenarios presented in Figure 3. (It does not show the results for no liming, as the rates are zero by definition.) Figure 3 was based on rainfall of 325-450 mm per year, but Table 1 also includes results for high and lower rainfall zones. In broad terms, optimal lime usage is lowest where only the surface soil is acidic, highest where the sub-soil is acidic but only surface application is used, and intermediate where both surface and sub-surface lime application is 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 sub-surface application, through incorporation of lime into the soil. When sub-surface application is used, the total amount of lime used in the first year can be reduced: from 8-10 tonnes per hectare, to 3-4 tonnes per hectare. This reflects the limited and delayed capacity of surface liming to improve sub-soil acidity.

The effect of rainfall on optimal liming practices is complex. First, where surface application of lime is used to treat sub-surface acidity, optimal surface application rates are lower at higher rainfall levels. This is because greater rainfall helps to transport lime into the soil. Second, where lime is incorporated into the acidic sub-soil layer, optimal surface rates, in particular maintenance rates, are greater at higher rainfall levels. This increase is related to the higher nitrogen leaching factors and consequently acidification rates at higher rainfall levels in subsequent years. This trend is more emphasised when surface and sub-surface 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 surface soil is more acidity, facilitating greater movement of lime to lower soil horizons.

Table 1. Optimal lime application rates (t ha^{-1}) with 10 year liming frequency for different acidic soil layers, rainfall and liming options

Rainfall (mm)	Acidic soil layer	Liming option	Surface rate (year 1) (t ha^{-1})	Subsurface rate (year 1) (t ha^{-1})	Surface maintenance rate (10 yearly) (t ha^{-1})
<325	Top	Surface	0.6	0.0	0.0
		Surface and subsurface	0.6	0.0	0.0
	Sub	Surface	10.1	0.0	0.0
		Surface and subsurface	0.1	1.6+1.6[a]	0.1
	Both	Surface	8.6	0.0	0.0
		Surface and subsurface	0.8	1.5+1.5	0.1
325-450	Top	Surface	0.6	0.0	0.2
		Surface and subsurface	0.6	0.0	0.2
	Sub	Surface	9.6	0.0	0.0
		Surface and subsurface	0.2	1.6+1.6	0.5
	Both	Surface	8.1	0.0	0.0
		Surface and subsurface	0.9	1.4+1.4	0.5
>450	Top	Surface	0.6	0.0	0.7
		Surface and subsurface	0.6	0.0	0.7
	Sub	Surface	9.4	0.0	0.1
		Surface and subsurface	0.6	1.6+1.6	0.9
	Both	Surface	7.8	0.0	0.5
		Surface and subsurface	1.4	1.4+1.4	0.9

[a] Optimal lime application rate was incorporated equally to two subsoil layers 10-20cm and 20-30cm

Most of the optimal lime application rates are influenced only slightly by changing lime application frequency from 10-yearly to 20-yearly. All of the optimal application rates for year 1 are the same or only slightly increased when the frequency is reduced (compare Table 1 and 2). The increases in optimal maintenance rates were larger, approximately doubling in all cases, as would be expected from a halving of frequency.

Table 2. Optimal lime application rates (t ha^{-1}) with 20 year liming frequency for different acidic soil layers, rainfall and liming options

Rainfall (mm)	Acidic soil layer	Liming option	Surface rate (year 1) (t ha^{-1})	Subsurface rate (year 1) (t ha^{-1})	Surface maintenance rate (20 yearly) (t ha^{-1})
<325	Top	Surface	0.6	0.0	0.0
		Surface and subsurface	0.6	0.0	0.0
	Sub	Surface	10.1	0.0	0.0
		Surface and subsurface	0.2	1.6+1.6[a]	0.2
	Both	Surface	8.6	0.0	0.0
		Surface and subsurface	0.9	1.5+1.5	0.2
325-450	Top	Surface	0.7	0.0	0.4
		Surface and subsurface	0.7	0.0	0.4
	Sub	Surface	9.6	0.0	0.0
		Surface and subsurface	0.5	1.5+1.5	1.0
	Both	Surface	8.1	0.0	0.0
		Surface and subsurface	1.2	1.4+1.4	1.0
>450	Top	Surface	0.8	0.0	1.6
		Surface and subsurface	0.8	0.0	1.6
	Sub	Surface	9.4	0.0	0.3
		Surface and subsurface	0.9	1.5+1.5	2.1
	Both	Surface	7.8	0.0	1.0
		Surface and subsurface	1.6	1.4+1.4	2.1

[a] Optimal lime application rate was incorporated equally to two subsoil horizons 10-20cm and 20-30cm

3.1.3 NPV responses

Table 3 shows NPVs for each scenario, for both 10- and 20-year lime application frequencies. Sub-soil acidity has a bigger 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 sub-surface 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.

Applying lime is substantially more profitable than not applying it (see Table 4). Surface lime application, relative to no lime application, increases profit by 1-7% in topsoil acidity condition and 55-92% in sub-soil acidity condition depending on rainfall levels. If there is sub-soil acidity, the best solution is to combine surface and sub-surface lime application; this results in up to 96% more benefit compared no lime application. Compared to surface liming only, the additional benefit of also sub-surface liming is small – less than 5% in all cases but one (see extra benefits for surface and sub-surface liming (%) in Table 3). In other words, the additional costs of sub-surface liming almost cancel out the additional benefits.

Table 3. NPV ($\$\ \text{ha}^{-1}$) response to different acidic soil layers, rainfall, liming options and frequency

	Frequency	Liming option	Rainfall (mm) <325			325-450			>450		
			Acidic soil layers								
			Top	Sub	Both	Top	Sub	Both	Top	Sub	Both
NPV($\$\ \text{ha}^{-1}$)	10	No Lime	8589	5113	5068	10377	5786	5735	12597	6827	6766
		Surface	8648	7934	8122	10569	9955	10106	13436	12895	13018
		Surface and subsurface	8648	8486	8467	10569	10394	10377	13436	13255	13239
Extra benefit for surface and subsurface liming relative to surface liming (%)			0.0	7.0	4.3	0.0	4.4	2.7	0.0	2.8	1.7
NPV($\$\ \text{ha}^{-1}$)	20	Surface	8648	7934	8122	10569	9955	10106	13437	12897	13024
		Surface and subsurface	8648	8486	8467	10569	10394	10377	13437	13252	13238
Extra benefit for surface and subsurface liming relative to surface liming (%)			0.0	7.0	4.3	0.0	4.4	2.7	0.0	2.7	1.6

Table 4. Ratio of NPV with and without lime application

Liming option	Rainfall (mm) <325			325-450			>450		
	Acidic soil layers								
	Top	Sub	Both	Top	Sub	Both	Top	Sub	Both
No Lime	1	1	1	1	1	1	1	1	1
Surface	1.01	1.55	1.60	1.02	1.72	1.76	1.07	1.89	1.92
Surface and subsurface	1.01	1.66	1.67	1.02	1.80	1.81	1.07	1.94	1.96

3.2 Sensitivity analysis

Due to the uncertainty involved in the estimation and specification of key parameters and bounds within the model, the sensitivity of the key results (optimal lime application rates and the NPV) to alternative values of selected parameters and bounds is examined. All sensitivity analyses presented are for the 325-450mm rainfall region under 10-yearly surface liming as it is the most common liming method in the study area.

3.2.1 Initial soil pH

Optimal lime rates in the base model are extremely sensitive to changes of initial pH (Table 5). The first row of results is for acidic condition in all three soil 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 (10-yeraly). Further increases in pH gradually decrease the surface rate in year one and increase the surface maintenance rate in the following years. The first step-change in pH has a large impact on NPV, but after the second step, the benefit of additional increases in pH is very small. These results reinforces the importance of initial soil pH as one of the key parameters in determining the optimal decision rules for lime application.

Table 5. Optimal lime application rate (t ha^{-1}) and NPV (\$ ha^{-1}) responses to alternative values of initial soil pH ($CaCl_2$) (325-450mm rainfall region under 10-yearly surface liming)

Initial pH ($CaCl_2$)			Surface rate (year 1) (t ha^{-1})	Surface maintenance rate (10 yearly) (t ha^{-1})	NPV (\$ ha^{-1})
0-10cm	10-20cm	20-30cm			
4.6	3.8	4.1	8.1	0	10106
4.8	4	4.3	4	0	10415
5	4.2	4.5	1.8	0.4	10521
5.2	4.4	4.7	0.7	0.7	10548
5.4	4.6	4.9	0.1	0.7	10563
5.6	4.8	5.1	0	0.6	10572

3.2.2 Wheat and lime prices

Both lime rates and NPV are highly sensitive to wheat prices but much less sensitive to lime prices. The impacts of ± 30% change in both wheat and lime prices on optimal lime rates and NPV responses are given in Table 6. The simultaneous change in prices: +30% change in wheat price and -30% change in lime price greatly increases lime rate and NPV.

Table 6. Optimal lime application rate (t ha^{-1}) and NPV ($ ha^{-1}) responses to ± 30% change in both wheat and lime prices (325-450mm rainfall region with top and subsoil acidity under 10-yeraly surface liming)

Surface rate (year 1) (t ha^{-1})

	Lime price (% change)		
Wheat price (% change)	-30%	Base case	+30%
-30%	7.2	6.9	6.6
Base case	8.5	8.1	7.7
+30%	9.6	9.2	8.7

NPV ($ ha^{-1})

	Lime price (% change)		
Wheat price (% change)	-30%	Base case	+30%
-30%	7031	7011	6992
Base case	10130	10106	10084
+30%	13239	13212	13186

3.2.3 Distance from lime pit and discount rate

Optimal surface lime application rate in year one is very sensitive to distance from lime pit but less sensitive to discount rate (Table 7). For instance, every 100 km increase in the distance from lime pit decreases the initial surface lime rate by around one tonne per hectare; however, it yields no change in the lime maintenance rates in the following years.

Table 7. Optimal lime application rate (t ha^{-1}) and NPV ($ ha^{-1}) responses to alternative values of selected parameters (325-450mm rainfall region with top and sub-soil acidity under 10 yearly surface liming)

Parameter	Surface rate (year 1) (t ha^{-1})	Surface maintenance rate (10 yearly) (t ha^{-1})	NPV ($ ha^{-1})
Base case: Distance from lime pit (100km) and Discount rate (5% real)	8.1	0	10106
Distance from lime pit (200km)	7.1	0	10035
Distance from lime pit (300km)	6.4	0	9971
Discount rate (10% real)	7.7	0	4836

3.2.4 Bound on lime rate

When there is sub-soil acidity but only surface liming is used, optimal rates are much higher than what farmers in the study region actually do. For example, optimal surface liming rates in year one given sub-soil acidity or both top- and sub-soil acidity conditions are about 8-10 t ha^{-1}. It is interesting to explore results where lime rates are constrained to lower, sub-optimal levels, more in line with current farming practices. For both 10-yearly and 20-yearly lime application frequency, substantial reductions in initial lime rate are possible with minimal impacts on profit (Table 8). For example, reductions in rates from 8-10 t ha^{-1} to 4 t ha^{-1} reduces NPV by only 2%. 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 this region apply less than optimal rates of lime is of little economic importance.

Table 8. Changes (%) in NPV for alternative upper bounds on lime rate (t ha^{-1}), relative to base case (upper bound on lime rate=30 t ha^{-1}), for 325-450mm rainfall region for different acidic soil layers under different surface liming frequency

Upper bound on lime rate (t ha^{-1})	Frequency 10 yearly			Frequency 20 yearly		
	Acidic soil layer					
	Top	Sub	Both	Top	Sub	Both
2	0	-7	-8	0	-9	-11
3	0	-4	-4	0	-4	-4
4	0	-2	-2	0	-2	-2
5	0	-1.2	-0.7	0	-1.2	-0.7
6	0	-0.6	-0.2	0	-0.6	-0.2

Liming is important in soil acidity management and has major impacts on crop production (Holland et al., 2018). The specific rate, or application method, or frequency are not so important, as they do not affect NPV much, but liming at a broadly appropriate rate is much more profitable than not liming. Lime application is a long-term investment, which might make it less attractive to farmers who have short planning reasons, such as farmers with limited finances, leased land or share farms. These farmers may be unwilling to invest in economically optimal levels of lime due to the time delay in the payback in lime investment. Diversity in farmers' attitudes and inclinations and their influence on the choice of a farming method is highlighted by Darnhofer et al. (2005).

In this study, we have looked at liming 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 that have not been represented here such as greenhouse gas emissions. Soil acidity threatens ecosystem health and liming with an important mitigation rule has been considered as the most common remedy (Holland et al., 2018; Lawrence et al., 2016). The dissolution of lime can be a net sink for CO_2 in soils with high pH, but a net source of CO_2 in acidic soils (West and McBride, 2005). However, avoiding applying lime to mitigate greenhouse gas emissions can result in other adverse environmental effects like soil acidification. The physical availability of lime is also limited, and this could create problems for farmers in future.

4 Conclusions

This study applies a dynamic optimization model to explore optimal lime application rate and frequency to manage soil acidity over different soil horizons in different rainfall regions of the Wheatbelt in Western Australia. Optimal lime application rate and frequency depend on rainfall level, soil acidity severity, and liming methods. A higher lime rate and frequency is required to amend soil acidity in high-rainfall agricultural zone in particular with acidic condition in both top and sub-soil horizons. Either 20-year or 10-year intervals between lime applications result in almost the same net returns to lime application, although, they slightly affect optimal lime application rates. The baseline results indicate that with either of the available lime application methods, soil acidity problem could be removed as a production constraint by applying lime at an appropriate application rate. Integration of surface and subsurface lime application methods results in in a slightly higher NPV compared with surface-only application, but probably not by enough to make sub-surface application a compelling option for most farmers.

Optimal decision rules are relatively sensitive to changes in a number of important economic parameters (wheat and lime prices, distance from lime pit and discount rate) and extremely sensitive towards the initial soil pH. The sensitivity analysis also highlights the importance of checking the flatness of the payoff functions in determining optimal lime decision rules. Although the unconstrained model results indicate that very high initial lime rates are optimal, we find that much lower rates, more in line with farmer practice, are only slightly less profitable.

All of the results presented here are based on a model in which the yield potential is the same each year, based on an average yield for an average year. We have not explored the consequences of year-to-year climatic variability for this management decision. We also have not analysed externalities associated with this decision.

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