Optimal lime rates for soil acidity mitigation: impacts of crop choice and nitrogen fertilizer in Western Australia¹

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The economics of liming and nitrogen-related practices are inter-related because nitrogen-related practices, including fertilizers and legume crops, affect soil acidification. This study presents insights from a dynamic economic optimization model that simultaneously determines optimal strategies for lime application, nitrogen application and legume crop rotation in Western Australia. The most profitable liming rate is sensitive to nitrogen fertilizer type and legume rotation, and optimal rates for both lime and fertilizer increase with rainfall.

Abstract

Many agricultural soils are naturally acidic, and agricultural production can acidify soil through processes such as nitrogen fixation by legumes and application of nitrogen fertilizer. This means that decisions about mitigation of soil acidity (e.g. through application of lime), crop rotation and nitrogen fertilizer are interdependent. This paper presents a dynamic model to determine, jointly, the optimal lime application strategies and nitrogen application rates in a rain-fed cropping system in Western Australia. The model accounts for two crop rotations (with and without a legume break crop), for the acid-tolerance of different crop types, and for differences in the acidifying effect of different nitrogen fertilizers. Results show that liming is a profitable strategy to treat acidic soils in the study region, but that there are interactions between nitrogen and acidity management. The choice of fertilizer affects optimal lime rates substantially, with the use of a more acidifying ammonium-based fertilizer leading to higher lime rates. The optimal liming strategy is also sensitive to inclusion of a legume crop in the rotation, as its fixed nitrogen can be less acidifying than fertilizer, and allows a reduction in fertilizer rates. Higher rainfall zones have greater nitrogen leaching, which contributes to a higher optimal rate of lime. We find that the injection of lime into the sub-soil is profit increasing. Optimal lime rates in the absence of sub-soil incorporation are higher than usual current practice, although the economic gains from increasing rates are small.

Keywords

Economics; lime requirements; modeling; nitrogen; rotation; soil acidification

1. Introduction

It is estimated that about 30 percent of arable lands worldwide have acidic soils (Rengel 2003), resulting in reduced crop production (Holland et al. 2018). Soil acidification is increased by agricultural production due to cation leaching, removal of cations in

harvested grain, application of nitrogen fertilizers, and the release of nitrogen from the breakdown of leguminous crops in the soil (Filippi et al. 2018). Soil acidity can increase crop exposure to certain toxic elements and restricts access to essential nutrients. In particular, crops growing in acidic soils can suffer from aluminium and manganese toxicity, and from calcium, magnesium, molybdenum, and phosphorus deficiency (Mullen 2001).

Agricultural lime (crushed limestone, CaCO_3 , and crushed dolomite, $\text{MgCa}(\text{CO}_3)_2$) have been used for centuries to mitigate soil acidity (Dodgshon 1978). Lime is traditionally applied to the soil surface and is assimilated gradually into the soil profile over a number of years (West and McBride 2005). The direct incorporation of lime into the sub-surface soil has shown promising results (Gazey et al. 2014a). Globally, sub-soil acidity in agricultural soils has been increasing, and application of lime has been insufficient to prevent it (FAO 2015). In Australia, top and sub-soil acidity has been increasing (Davies et al. 2015; Gazey et al. 2014a; Gazey et al. 2014b; Gazey and Ryan 2015).

Studies have examined the interaction between liming and fertilizer application in determining grain yield. Most studies have observed that lime and fertilizer are complementary inputs, in that lime increases the marginal product of fertilizer (Bekele et al. 2018; Holland et al. 2018; Tumusiime et al. 2011; Wang et al. 2003). There have been a small number of studies with contrasting results (e.g., Bolton et al. (1976)), but overall, a positive interaction is the usual result. Optimal decisions on lime and fertilizer should be taken jointly and account for dynamics. However, most studies are static and consider decisions separately for lime (e.g., Bongiovanni and Lowenberg-DeBoer (2000); Lukin and Epplin (2003); Mulungu et al. (2013)) and fertilizer (e.g., Adams et al. (2000); Basso et al. (2011); Biermacher et al. (2006); Robertson et al. (2008); Wang et al. (2014); Zhao et al. (2006)). An additional consideration is that nitrogen fertilizer can acidify soil if it leads to nitrate leaching. Furthermore, fertilizers that contain nitrogen in the form of ammonium (e.g., di-ammonium phosphate, ammonium sulfate etc.) are acidifying even

if no nitrate is leached (Malhi et al. 2000). This may affect the optimal fertilizer rate as well as the optimal liming strategy.

Another complexity affecting lime strategies is the sequence of crops. Crops differ in their tolerance of acidity (Fageria et al. 2010), and they have different response to nitrogen fertilizer in acidic conditions (Rajneesh et al. 2018). It has been shown that, in the presence of soil acidity, diverse crop sequences containing acid-tolerant and acid-sensitive crops lead to more stable net farm income and better economic performance compared to mono-cultural systems (Kirkegaard et al. 2008; Zentner et al. 2002). On the other hand, just as with nitrogen fertilizer, any nitrogen fixed by legumes that ends up leaching as nitrate also leads to acidification. For both these reasons, the sequence of crops could influence optimal lime rates, but this too has not previously been studied. The effect of acidification on the optimal crop rotation has also not been assessed.

The rate at which lime neutralizes acidity throughout the soil profile depends on moisture availability (Goulding 2016). Furthermore, soil acidification caused by the removal of cations in harvested grain is directly linked to crop yield, and yields in turn are often strongly linked to climate. Finally, the adverse effects of acidity on crop yield and response of crop yield to liming can be greater in high rainfall than low rainfall zones (Tang et al. 2003; Wong et al. 2008). As a consequence, optimal liming strategies will vary by region depending on rainfall.

The objective of this study is to determine optimal liming strategies accounting for the above complexities: the interaction between fertilizer and acidity, the different acidification rates of different nitrogen fertilizers, the differing acid tolerance of different crops, the acidifying effect of nitrogen fixed by legumes, the depth of lime application, and the effect of rainfall. The strategies evaluated encompass different rates of liming, different frequencies of lime application, and different methods of lime application (surface versus surface plus sub-surface), as well as different rates of nitrogen fertilizer.

The analysis is applied to a case study: three regions of the Western Australian wheatbelt with different levels of rainfall. The analysis employs a dynamic optimization model that maximizes the Net Present Value (NPV) of net income from crop production.

2. Method

2.1 Study area and farming system

The approximately 155,000 km² Western Australian wheatbelt is located in the south-west of Australia. Farming systems in the wheatbelt are dominated by cropping. The region produces about 14 million tonnes of grain annually (Wilkinson 2018). About 81% of the cropped area is sown to cereals (usually wheat, but also barley and oats) (ABS 2017). The two main break crops used to complement cereals are narrow-leaved lupin (a legume) and canola (Seymour et al. 2012). This region has a Mediterranean climate with hot, dry summers and cool to mild, wet winters. About 75% of annual rainfall occurs between May and October. Sand and duplex (sand over clay) are the most common soil types in the region (Schoknecht and Pathan 2013).

Soil acidity (and associated aluminium toxicity) is a significant issue in the wheatbelt and more than 70% of topsoils and 50% of sub-soils have a pH lower than minimum target of between 5.5 and 4.8 recommend by local farm extension services (Gazey et al. 2013). Indeed, elevated soil acidity, in particular sub-soil acidity, is estimated to reduce farm revenue by \$A1.6 billion year⁻¹ in grain-producing regions of Western Australia (Petersen 2015).

For this study, three different rainfall zones from the northern part of the wheatbelt were selected: low rainfall (<325 mm annual average), medium rainfall (325 to 450 mm annual average), and high rainfall (>450 mm annual average). This study focuses on the sandy soil (a yellow sandy-textured topsoil horizon over sandy-loam sub-soil horizons) as this tends to be more acidic (Petersen 2015). In this study, three different acidified soil

profiles are considered: an acidic topsoil (0-10 cm)², an acidic sub-soil (10-30 cm), and both top and sub-soil acidic (0-30 cm). Sub-soil is taken as meaning soils in the 10-20 and 20-30 cm horizons where 'acidic' soil is taken to mean initial 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 initial pHs of 5.8, 5.8 and 6.5, respectively (see Figure 1). All pH values in this study refer to pH measured in CaCl₂.

Figure 1.

2.2 Model structure

A dynamic optimization model is developed to determine optimal lime and nitrogen fertilizer application rates, liming frequency and lime application method in each of the case-study zones. A perpetually-repeated three year sequence of either wheat, wheat, lupins (WWL) or wheat, wheat, canola (WWC) are modeled. The model was constructed in GAMS (General Algebraic Modeling System) and solved using the CONOPT algorithm (Drud 1996). The model consists of a biophysical component, largely derived from an existing simulation model, Optlime (Gazey 2008), and an economic component (Figure 2).

Figure 2.

Optlime is a simulation model that predicts soil pH responses to lime application, and acidifying processes associated with nitrogen fertilizer use, legumes (if applicable) and the removal of agricultural produce (Oliver et al. 2014). Based on the biophysical component shown in Figure 2, monthly soil pH dynamics across three different soil horizons (0-10 cm, 10-20 cm and 20-30 cm) are determined through integrating information on soil characteristics (soil initial pH, gravel content, bulk density, organic

² The occurrence of an acidic topsoil without the subsoil also being acidic is a relatively uncommon scenario in the study area but is included to broaden the theoretical coverage of this research.

carbon, aluminium level, and texture) with information on crop type, rainfall, nitrogen fertilizer rate and type (urea and ammonium sulfate), the nitrogen contained in legume residues (where applicable) and also information on lime quality, rate and application method (surface and sub-surface). Crop yield is then predicted based on the average soil pH over the May to October-growing season (plus rainfall and nitrogen fertility levels). More detailed information on soil pH dynamics can be found in Shoghi Kalkhoran et al. (2018).

The dynamic optimization is run over 80 years to allow the system to reach a steady state. 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.. The model determines the optimal nitrogen fertilizer rate for each crop, a corrective/initial lime application rate for year one, and subsequent optimal maintenance applications. Maintenance applications are fixed at 10 year intervals (previous research has shown this is the optimal liming frequency in the study area, and furthermore, that profit is insensitive to application frequency (reference suppressed for anonymity)). To improve the model's tractability when solving, the rate for all maintenance applications is constrained to be equal (i.e., to be constant through time). For each given crop phase in the rotation sequence (e.g., for wheat grown the year after canola) nitrogen applications were also constrained to be constant through time, again for tractability reasons.

The model's optimization problem can be written as:

$$\max_{\{l_{t,i} \text{ and } N_{fert_t}\}} NPV = \sum_{t=1}^T \left\{ \left[(p_{crop} \times y_t) - (p_{fert} \times N_{fert_t}) - w_t \right] (1+r)^{-t} \right\} +$$

$$\sum_{t=T-\Psi}^T \frac{\{[(p_{crop} \times y_t) - (p_{fert} \times N_{fert_t}) - w_t](1+r)^{-t}\}}{((1+r)^{\Psi}-1)} \quad (1)$$

subject to equations (2) to (15)

where NPV is the net present value of returns (\$ ha⁻¹) to the crop grower over the T (80) years of the time horizon; $l_{t,i}$ is the lime application rate in a given year, applied to a given soil horizon (0-10 cm, 10-20 cm and 20-30 cm), i , once a year in January; p_{crop} is the grain price of the crop being grown in the rotation in year t (\$ t⁻¹); y_t is the yield of the crop being grown in the rotation in year t (t ha⁻¹); p_{fert} is the nitrogen fertilizer price (\$ kg fertilizer⁻¹); N_{fert_t} is the amount of nitrogen fertilizer applied in a given year (kg fertilizer ha⁻¹); w_t is the total cost of lime and its application (\$ ha⁻¹); and r is real discount rate, set at 5%. Ψ is the frequency of maintenance lime applications (10 years). The second part of the equation (1) is the net present value of the last Ψ years of the planning horizon assuming that their returns are repeated in perpetuity. This terminal value function is to account for economic values of lime and nitrogen fertilizer application after the modeled time horizon.

2.3 Nitrogen and yield responses

Unless otherwise stated, the response of wheat and canola to nitrogen fertilizer in either rotation is modeled using equations and parameters from Adams et al. (2000), who in turn utilised the previous work of Angus et al. (1993), Burgess et al. (1991) and Bowden and Burgess (1993). The yield (t ha⁻¹), y_t , of non-legume crops (wheat and canola) in each year t is given by:

$$y_t = y^{Potential} \times \gamma_t^{total} \times N_{sc_t} \quad \forall t = 1, \dots, T \quad (2)$$

where $y^{Potential}$ is the yield potential (t ha⁻¹) that can be achieved in an average-rainfall year (disregarding the variations from year to year in rainfall and yield) if acidity and

nitrogen fertility are not limiting production. It is used to account for all other factors that affect yield but are not explicitly represented in the model, such as sowing time, status of other nutrients, diseases, and weeds. Based on the Planfarm Bankwest series of annual reports (e.g., Bankwest (2016)), $y^{\text{Potential}}$ for the three rainfall regions (low, medium and high) is 1.8, 2.2, and 2.8 t ha⁻¹ for wheat, 1.01, 1.27, 1.57 t ha⁻¹ for canola, and 1.08, 1.48, and 1.69 t ha⁻¹ for lupin respectively. The impact of pH on yield is captured by γ_t^{total} , which has a value between 0 and 1 and is calculated as the product of three pH scalars for the 0-10 cm, 10-20 cm and 20-30 cm soil horizons (Gazey 2008). N_{sc_t} represents the proportion of a non-legume crop's yield potential can be realised accounting for nitrogen fertility. N_{sc_t} also takes a value between 0 and 1, and is given by:

$$N_{sc_t} = 2 \times \frac{N_{up_t}}{a1 \times y^{\text{Potential}}} - \left(\frac{N_{up_t}}{a1 \times y^{\text{Potential}}} \right)^2 \quad \forall t = 1, \dots, T \quad (3)$$

where $a1$ is equal to 0.04 for wheat and 0.07 for canola. The term N_{up_t} represents nitrogen uptake in a given year (in kg ha⁻¹), calculated as:

$$N_{up_t} = N_{max} \times \tanh\left(\frac{N_{avail_t}}{N_{max}}\right) \quad \forall t = 1, \dots, T \quad (4)$$

$$N_{max} = a2 \times y^{\text{Potential}} \quad (5)$$

where N_{max} is the maximum uptake of nitrogen that could occur if the nitrogen supply in the soil was unlimited; $a2$ is a parameter, set to 0.06 for wheat and 0.07 for canola; N_{avail_t} is the amount of nitrogen available in a given year for plant uptake, calculated as:

$$N_{avail_t} = K_{fert_t} \times N_{fert_t} + K_{SON_t} \times N_{SON} + K_{RON_t} \times N_{RON_t} \quad \forall t = 1, \dots, T \quad (6)$$

where K_{fert_t} , K_{SON_t} and K_{RON_t} represent the proportion of three different sources of nitrogen, N_{fert_t} , N_{SON} , and N_{RON_t} , that become available to the crop over a growing

season. N_{fert_t} , N_{SON} , and N_{RON_t} , all expressed in kilograms of elemental nitrogen (kg N) where: 1) N_{fert_t} is the amount of nitrogen fertilizer applied in a given year, either in the form of urea ($CO(NH_2)_2$, 46% N) or ammonium sulfate $(NH_4)_2SO_4$, 21% N). 2) N_{SON} is 'stable organic nitrogen' which is the pool of nitrogen contained in the soil's organic matter. The proportion of N_{SON} that is actually available to the crop over a growing season (K_{SON_t}) is small. N_{SON} is estimated from the level of organic carbon in the soil:

$$N_{SON} = ((1667 \times \rho^{soil}) \times C)(1 - \xi) \times \frac{1}{CN_{SON}} \times 1000 \quad (7)$$

where ρ^{soil} is the 0-10 cm soil bulk density ($g\ cm^{-3}$), set to be 1.5; C is the 0-10 cm soil organic carbon content ($g\ cm^{-3}$), which is set to be 0.007, 0.008 and 0.010 for the low, medium and high rainfall zones respectively (NLWRA 2001); ξ is the fraction of the 0-10 cm soil horizon that is made up of gravel (small rocks), set to be 0.05; and CN_{SON} is the carbon/nitrogen ratio of the soil, set to be 15 (Adams et al. 2000); It is also assumed that 60% of the total N_{SON} pool occurs in the 0-10 cm soil horizon. 3) N_{RON_t} represents the residue organic nitrogen derived from the previous legume crop. Thus, in the present analysis, N_{RON_t} is only a source of nitrogen in the case of the WWL rotation. For the first wheat crop following lupin, N_{RON_t} is calculated as follows:

$$N_{RON_t} = \frac{y_t^{lupin}}{L_{HI}} \times L_{Nbm} - y_t^{lupin} \times L_{Ng} \quad \forall t = 1, \dots, T \quad (8)$$

and for the second wheat crop after lupin, N_{RON_t} is greatly reduced (by a factor of $\frac{1}{3}$ —Bowden and Burgess 1993) and is thus predicted by:

$$N_{RON_t} = \left(\frac{y_t^{lupin}}{L_{HI}} \times L_{Nbm} - y_t^{lupin} \times L_{Ng}\right) \times \frac{1}{3} \quad \forall t = 1, \dots, T \quad (9)$$

where y_t^{lupin} is the yield (in $kg\ ha^{-1}$) of the previous lupin crop in the WWL rotation. The variable y_t^{lupin} is endogenously predicted by the model based on the equation (2) though

without the N_{sc_t} parameter because no nitrogen fertilizer is applied to lupin. L_{HI} is the harvest index of the lupin crop, assumed to be 0.25 (Bowden and Burgess 1993); L_{Nbm} is the proportional nitrogen content of the lupin crop residues and is set at 0.0275 (Schultz and French 1978); L_{Ng} is the nitrogen concentration of the lupin grain, assumed to be 0.05 (White et al. 1981).

K_{fert_t} , K_{SON_t} and K_{RON_t} vary with rainfall (due to leaching), and soil pH (due to the impact of acidity on rooting, and thus nutrient use efficiency) according to the following formula (which was derived based upon the results of simulations in the SYN model (Bowden and Diggle 2003)):

$$K_{fert_t}, K_{SON_t} \text{ and } K_{RON_t} = \frac{\exp(-64.4826 + 13.7197 * pH_{t,20-30cm})}{(1 + \exp(-64.4826 + 13.7197 * pH_{t,20-30cm}))} \times b1 + b2 \quad \forall t = 1, \dots, T \quad (10)$$

where $pH_{t,20-30cm}$ is the pH measured at the end of growing season of a given year for 20-30 cm of soil horizon. Note that the three K variables are all calculated with equation (10), but with different $b1$ and $b2$ constants (Table 1). The values used for $b1$ and $b2$ are shown in the first three columns of Table 1 labelled K_{fert_t} , K_{SON_t} and K_{RON_t} .

Table 1.

2.4 Nitrogen and acidification rate

Acidification occurs firstly due to the removal of harvested materials and, secondly due to the nitrogen cycle. Acidification due to the removal of harvested products is expressed in terms of the 'alkalinity export rate' (in kg $CaCO_3$ equivalent t^{-1} of harvested grain) which was set to 2.25 for wheat and canola, and 12.5 for lupin (Gazey 2008). The acidification rate in a given year (expressed in kg $CaCO_3$ ha^{-1}) due to the nitrogen cycle depends on the source of nitrogen (e.g., different fertilizers and also legume-fixed nitrogen), and

extent of nitrogen leaching. Based on Gazey (2008) the acidification rate for lupin is calculated as:

$$Acidification\ rate_t = N_{acid} \times N_{leach_t} \times y_t^{lupin} \times 60 \quad \forall t = 1, \dots, T \quad (11)$$

And for non-legume crops fertilized with urea it is calculated as:

$$Acidification\ rate_t = N_{acid} \times N_{leach_t} \times N_{fert_t} \quad \forall t = 1, \dots, T \quad (12)$$

Because ammonium-based fertilizers are acidifying, for non-legume crops fertilized with ammonium sulfate, the acidification rate is calculated as:

$$Acidification\ rate_t = (3.6 + (N_{acid} \times N_{leach_t})) \times N_{fert_t} \quad \forall t = 1, \dots, T \quad (13)$$

where N_{acid} is 3.6 for urea and legume-fixed nitrogen, and 3.5 for ammonium sulfate (Gazey 2008). N_{leach_t} is the percent of the nitrogen source in question that is leached down the soil profile, beyond the reach of the crop's roots in the given year t . N_{leach_t} varies with nitrogen source, soil pH and rainfall, as captured in the following formula (which was derived from the results of simulations in Bowden and Diggle (2003)):

$$N_{leach_t} = \frac{\exp(-64.4826 + 13.7197 \times pH_{t,20-30cm})}{(1 + \exp(-64.4826 + 13.7197 \times pH_{t,20-30cm}))} \times b1 + b2 \quad \forall t = 1, \dots, T \quad (14)$$

where $b1$ and $b2$ are constant leaching factors whose values depends on the source of N (fertilizer versus legume-fixed nitrogen) and rainfall, as shown in the last two columns of Table 1.

2.5 Prices and costs

The costs and prices of output and inputs are in Australian dollars (AUD) and assumed to remain constant in real terms for the duration of the time horizon. Based on the models

used by Thamo et al. (2017), farm-gate prices of wheat, lupin, canola (non-genetically modified) and urea are set to \$241, \$247, \$475 and \$660 t⁻¹, respectively (these align well with average long term real prices e.g., <http://agprice.grainandgraze3.com.au/>). Ammonium sulfate price is set to \$400 t⁻¹ at the farm gate. Liming costs were set based on Optlime (Gazey 2008), updated in consultation with farmers and contractors. The purchase price of the most widely applied lime product in the study area—lime-sand with 89.3% acidity neutralizing value lime—was set at \$10 t⁻¹ plus an assumed 100 km freight to the farm at a cost of \$0.1 km⁻¹ t⁻¹. The cost of surface application of lime is calculated on a per tonne basis and decreases as application rate increases, as follows:

$$\text{Surface application cost}_t = \frac{7.4}{(l_{t,i} + 0.09)} + 4.9 \quad \forall t = 1, \dots, T \quad i = 0 - 10 \text{ cm} \quad (15)$$

Sub-surface lime application modeled in this analysis involves ripping and then injecting bands of lime within the soil profile. Thus costs are more dependent on area than liming rate. Application costs, independent of liming rate, were estimated as \$123.72 (\$ ha⁻¹) including cost of ripping, injecting bands of lime within the soil profile, labour, and the machinery depreciation.

3. Result and discussion

For the WWC rotation both the optimal lime rates and the optimal nitrogen rates are generally higher as rainfall increases (Table 2). One factor driving this result is the higher yield potential of crops in higher-rainfall regions, which makes profit more responsive to production inputs. A second factor is that a higher rainfall level increases the rate of nitrogen leaching through the soil. This increases the need for nitrogen fertilizer (to replace that which has been leached) and it contributes to increasing the optimal rate of lime (because leaching of nitrogen causes acidification). A third factor is that crops in high rainfall conditions yield more, which results in greater acidification from product removal.

Results are sensitive to the type of nitrogen fertilizer used. Optimal nitrogen rates are lower if ammonium sulfate is applied rather than urea. This is largely because urea is cheaper per kg of nitrogen. (Ammonium sulfate does have the benefit of also supplying sulphur, but this benefit is not taken into account in this analytical framework – we assume that sulphur is not limiting yield).

Despite the lower rates of nitrogen applied as ammonium sulfate, it is associated with higher liming rates, because it is much more acidifying. Each kilogram of nitrogen applied as ammonium sulfate causes acidification that would require 3.6 and 7.1 kg of CaCO_3 to neutralize if 0% and 100% of nitrogen was leached, respectively. Urea, on the other hand, would cause no acidification in the absence of leaching and would require 3.6 kg of CaCO_3 to neutralize it if there is 100% leaching (Gazey 2008).

The optimal liming strategy depends critically on which layers of the soil are acidic. In most cases, the optimal placement of the initial (i.e., Year 1) lime application is aligned with which soil layers are acidic (Table 2). The exceptions are when only the sub-soil is acidic and rainfall is relatively high. The higher leaching of lime that occurs as a result of the higher rainfall means that it is optimal to apply some lime at the surface, despite the fact that the surface soil is not acidic.

The optimal rate for surface applied lime is usually lowest where only the surface soil is acidic, intermediate where only the sub-surface is acidic, and highest where both surface and sub-surface soil are acidic. In the first case (topsoil acidity only), lime needs to move only a short distance through the soil, so its effects on acidity are rapid and strong. Where deeper layers are acidic, higher levels of surface lime are optimal because there is more acidity to counter, and because the lime has to move a greater distance, which it does only slowly (Figure 3). Higher acidity in the sub-soil causes an increase in the optimal surface rate of lime in addition to sub-surface lime application (compare surface lime application rates for topsoil versus top and sub-soil acidity conditions in Table 2).

Whilst it is generally accepted that the amelioration of sub-soil acidity by surface-applied lime is likely to be very protracted (e.g. Li et al. 2019), the amelioration of sub-soil acidity by lime applied only to the soil surface shown in Figure 3 is relatively rapid. However, it can be explained. First, the sandy soil type modeled is poorly-buffered, meaning soil pH tends to be more responsive to lime applications. For instance, Mason et al. (1994) found 3 t ha⁻¹ lime applied to the 0-10 cm layer increased the pH of the 10-20 cm layer within two years in loamy sands of the West Australian wheatbelt. Second, the optimal rates of surface-applied lime in Figure 3 to the low and high rainfall scenarios is 15.1 and 9.9 t ha⁻¹ respectively, which is much higher than rates typically applied commercially, or even in field trials (e.g. Whitten et al. 2000). At higher rates, the depth and movement of surface-applied lime is greater (Conyers et al. 2003). The role of rainfall is also evident in Figure 3. With less rainfall to aid the downward movement of lime, the optimal lime rate for the low rainfall (15.1 t ha⁻¹) is actually greater than the optimal rate for the high rainfall site (9.9 t ha⁻¹), yet the rate of sub-soil amelioration is nonetheless quicker for the high rainfall scenario.

Figure 3.

In all cases except one, it is economically beneficial to apply top-up or maintenance lime every 10 years at a relatively low rate. These maintenance applications are always to the surface rather than the sub-soil. Maintenance (decadal) sub-soil applications are an option in the model but not shown in the results tables as they were never part of the optimal solution in any circumstances.

Nitrogen fertilizer is applied every year, and the optimal rate is similar for wheat and canola. As noted earlier, the optimal rate depends mainly on rainfall and to a lesser extent on the type of nitrogen fertilizer used.

Table 3 shows the equivalent results for the WWL rotation. The most striking difference from Table 2 (i.e., the WWC results) is that the optimal rate of nitrogen fertilizer for the

wheat crop that immediately follows the leguminous lupin crop is substantially reduced – to half or less in most cases, relative to wheat in Table 2. As fixed nitrogen is less acidifying than nitrogen obtained from fertilizers (that is less prone to nitrogen leaching, see Table 1), optimal lime rates are reduced in the WWL rotation compared to the equivalent WWC rotation: by an average of 42 percent for the initial surface application, by 13 percent for the initial sub-surface application, and by 56 percent for the maintenance surface applications. In other respects, the liming strategies for WWL and WWC follow similar patterns.

Table 2.

Table 3.

Although the results presented so far show that incorporation of lime into the sub-soil is economically optimal in the long term, few farmers in the study region are doing this currently, at least with the ‘deep-banding’, direct injection of lime into the sub-soil method modeled in this analysis. Most apply lime only to the soil surface (Gazey et al. 2014a). To explore the consequences of this farmer practice, Tables 4 and 5 show results for the same scenarios as Table 2 and 3, except that the option of sub-soil lime application is removed. The model is re-optimized in case other aspects of the liming and fertilizer strategies are altered as a result.

For both rotations, removing the option for deep lime application causes substantial increases in the optimal surface lime rate. Across Tables 4 and 5, rates for the initial surface application are between three and 15 times higher, and average eight times higher, than they are in Tables 2 and 3, respectively. The optimal rates of nine to 17 tonnes of lime per hectare are far above the rates farmers are actually applying, which are typically one to two tonnes (Gazey et al. 2014b). With these much greater surface applications of lime initially, the optimal rates for the 10-yearly maintenance applications becomes lower. Indeed, for the low- and medium-rainfall regions, maintenance

applications are mostly no longer required (Tables 4 and 5). Restricting lime application to the surface and not the sub-soil makes very little difference to optimal rates of nitrogen.

Despite the large changes in optimal liming strategy when sub-surface liming is omitted, changes to profit are small to modest. Across both rotations, the resulting reductions in NPV ranged from 2 percent to 16 percent, with an average of 7 percent. Thus, the decision not to use deep incorporation of lime is not highly costly for most farmers. It is worth noting though that during process of deep-banding lime the soil profile is also ripped (at least to 30 cm deep). With sub-soil compaction a major issue in many of the sandy soils of the study region; the ripping during the deep-banding of lime may also be beneficial for the amelioration of compaction. However, whilst in this analysis the expense of this ripping is accounted for as part of the deep-banding cost, no benefit is attributed to reduced compaction, meaning estimates of the benefits of deep-incorporation are likely to be conservative in many circumstances.

Table 4.

Table 5.

Given that the optimal lime rates in Tables 4 and 5 are far above the rates normally used by farmers, it is worth asking what happens to farm profits if lower-than-optimal rates are used. Figure 4 shows the relationship between surface lime rate and NPV for each of the rotations, with the model constrained to exclude sub-surface liming. These results are for the intermediate rainfall zone, although results for the other zones are broadly similar. As is common for many agricultural inputs (Pannell 2006), the relationship between lime rate and NPV is remarkably 'flat' for large changes in lime rate. If the farmer with a WWC rotation used a lime rate of 6 t ha⁻¹ rather than the optimal 14.1 t ha⁻¹, the loss of NPV would be less than 5 percent. The relatively flat region does not extend down to the commonly used rate of 2 t ha⁻¹, which would suffer an 18 percent loss. For the WWL rotation, however, even the 2 t ha⁻¹ rate is only 7 percent less profitable than the

optimal rate of 9.7 t ha⁻¹. Consequently, although currently used rates are less than optimal, their financial performance is still strong, and they are far better than applying no lime. Farmers may appreciate the advice that a moderate increase in their lime rates would generate most of the benefits achievable by much larger increases to the economic optima.

Figure 4.

We have already explored the sensitivity of results to a range of factors, including rainfall, which soil layers are acidic, type of nitrogen fertilizer, use or non-use of sub-surface liming, and crop rotation. Finally, we investigate the impacts of price changes for the two relevant input types, lime and fertilizer. Table 6 shows the effects of these prices on the optimal initial lime rate (constrained to surface application only), the optimal nitrogen rate to apply to wheat, the percentage reduction in NPV if lime application is constrained to 2 t ha⁻¹, and the percentage increase in NPV if sub-surface incorporation of lime is allowed.

Table 6.

The optimal lime and nitrogen rates are sensitive to price changes in different ways. The optimal initial lime rate is somewhat affected by the lime price and slightly affected by the price of nitrogen via its effect on nitrogen application rates. The latter effect is substantial, with nitrogen rates ranging from 51 to 89 kg ha⁻¹ in response to price changes. On the other hand, the optimal nitrogen rate is almost unaffected by the lime price.

The effect of constraining the initial surface lime application rates to 2 t ha⁻¹ is relatively insensitive to price changes, ranging from 6 to 8 percent. Similarly, the benefit of allowing sub-surface liming is insensitive to either of the price changes, remaining at around 5 percent in all cases.

There are avenues for further research with this model. For instance, to reduce the

number of confounding factors the only factor varied between the three different soil profiles analyzed was initial pH. Investigation of more nuanced scenarios – such as different initial pHs simultaneous with inherently different pH buffering capacities – could be relevant to the real-world situation facing farmers in the study area, but is beyond the scope of the present analysis. Similarly, the trade-offs between different lime qualities (with different costs) and how they could affect the optimal strategy is relevant to farmers in the study area and a prospect for further investigation.

3. Conclusion

A dynamic optimization model has been used to explore optimal lime and nitrogen fertilizer application rates that maximize the NPV of farm net income for alternative crop rotations and nitrogen fertilizer types in the northern wheatbelt of Western Australia, a region with high soil acidity. There are important interactions between the management of acidity and nitrogen. In particular, the optimal liming strategy is affected by the type of nitrogen fertilizer applied, since different fertilizers are more or less acidifying. In addition, the economics of liming depend on whether the crop rotation includes a legume (lupin in this case), which can reduce the optimal application rates for acidifying nitrogen fertilizers. The level of rainfall causes a further interaction between nitrogen and acidity: the higher the average rainfall in the farming area, the greater is the level of leaching of nitrogen, which increases the optimal rate of lime to counteract the resulting soil acidification. The results highlight that sound understanding of the role of nitrogen, and accounting for the specific nitrogen-related practices used, is important for identification of optimal acidity-management practices.

We have identified two aspects of lime management where current practice by most farmers departs from the strategy that the model identifies as economically optimal. Firstly, incorporation of lime into the sub-soil, although costly, increases the NPV of crop production by reducing sub-soil acidity more effectively and more rapidly. However, the

loss of NPV from not practicing sub-soil liming is only small to moderate, averaging 7 percent across the range of scenarios examined. Secondly, in circumstances where lime is only applied to the surface, not the sub-surface, the optimal lime rate is found to be much higher than farmers use in practice. Again, however, the loss of NPV from using lower than optimal lime rates in these circumstances is found to be modest, particularly for the WWL rotation.

4. Conflicts of interest

The authors declare no conflict of interest.

5. Acknowledgements

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Table 1. The values taken for b1 and b2 in equation (10) and (14).

Rainfall (mm)		K_{SON_t}	K_{RON_t}	K_{fert_t}	Ammonium sulfate and urea leaching	Legume-fixed nitrogen leaching
<325	b1	0.001	0.01	0.04	-0.04	-0.03
	b2	0.021	0.26	0.59	0.38	0.19
325-450	b1	0.001	0.01	0.05	-0.06	-0.03
	b2	0.019	0.23	0.43	0.55	0.28
>450	b1	0.001	0.01	0.05	-0.05	-0.03
	b2	0.018	0.22	0.35	0.63	0.31

Table 2. Optimal combinations of nitrogen fertilizer rates and lime application rates with corresponding Net Present Values (NPV) for the WWC rotation.

Annual rainfall (mm)	Acidity condition	Nitrogen fertilizer	Lime application rate (t ha ⁻¹)			Nitrogen fertilizer rate (kg N ha ⁻¹)		NPV (\$ ha ⁻¹)
			Surface (year 1)	Sub-surface* (year 1)	Surface maintenance (10 yearly)	Wheat	Canola	
<325	Topsoil	Urea	1.3	-	-	55	55	\$6,642
		(NH ₄) ₂ SO ₄	2.0	-	1.0	43	42	\$6,115
	Sub-soil	Urea	-	3.8	0.6	54	54	\$6,465
		(NH ₄) ₂ SO ₄	-	6.2	1.8	42	41	\$5,901
	Top and sub-soil	Urea	1.7	3.0	0.3	55	55	\$6,445
		(NH ₄) ₂ SO ₄	3.0	3.8	0.9	43	42	\$5,908
325-450	Topsoil	Urea	1.1	-	0.6	82	84	\$7,346
		(NH ₄) ₂ SO ₄	2.5	-	1.5	62	63	\$6,586
	Sub-soil	Urea	1.7	3.2	0.6	81	84	\$7,162
		(NH ₄) ₂ SO ₄	3.3	3.8	1.4	60	62	\$6,376
	Top and sub-soil	Urea	2.3	3.0	0.6	82	84	\$7,151
		(NH ₄) ₂ SO ₄	3.4	3.4	1.4	62	63	\$6,383
>450	Topsoil	Urea	1.4	-	1.0	113	110	\$8,560
		(NH ₄) ₂ SO ₄	2.6	-	1.9	79	78	\$7,570
	Sub-soil	Urea	2.0	3.6	1.0	113	110	\$8,366
		(NH ₄) ₂ SO ₄	3.5	4.0	1.9	78	77	\$7,356
	Top and sub-soil	Urea	2.6	3.2	1.0	113	110	\$8,354
		(NH ₄) ₂ SO ₄	3.7	3.6	1.9	79	78	\$7,358

* This lime application is divided equally between the 10-20 cm and 20-30 cm soil horizons

Table 3. Optimal combinations of nitrogen fertilizer rates and lime application rates with corresponding Net Present Values (NPV) for the WWL rotation.

Annual rainfall (mm)	Acidity condition	Nitrogen fertilizer	Lime application rate (t ha ⁻¹)			Nitrogen fertilizer rate (kg N ha ⁻¹)		NPV (\$ ha ⁻¹)
			Surface (year 1)	Sub-surface* (year 1)	Surface maintenance (10 yearly)	Wheat after lupin	Wheat after wheat	
<325	Topsoil	Urea	0.6	-	-	28	46	\$6,493
		(NH ₄) ₂ SO ₄	1	-	-	15	33	\$6,270
	Sub-soil	Urea	-	3.4	0.1	27	43	\$6,319
		(NH ₄) ₂ SO ₄	-	3.4	0.8	15	33	\$6,073
	Top and sub-soil	Urea	1.2	2.8	-	27	45	\$6,299
		(NH ₄) ₂ SO ₄	0.8	3.4	0.3	16	34	\$6,061
325-450	Topsoil	Urea	0.6	-	0.4	38	67	\$7,748
		(NH ₄) ₂ SO ₄	0.8	-	0.7	17	47	\$7,448
	Sub-soil	Urea	1.3	3.0	0.4	37	67	\$7,562
		(NH ₄) ₂ SO ₄	1.7	3.2	0.6	16	46	\$7,254
	Top and sub-soil	Urea	1.9	2.8	0.4	37	67	\$7,551
		(NH ₄) ₂ SO ₄	2.2	3.0	0.6	17	47	\$7,246
>450	Topsoil	Urea	0.8	-	0.7	55	94	\$9,093
		(NH ₄) ₂ SO ₄	1.0	-	0.9	21	60	\$8,689
	Sub-soil	Urea	1.5	3.2	0.6	54	93	\$8,899
		(NH ₄) ₂ SO ₄	1.7	3.4	0.8	20	59	\$8,491
	Top and sub-soil	Urea	2.1	3.0	0.6	54	93	\$8,887
		(NH ₄) ₂ SO ₄	2.4	3.2	0.8	21	59	\$8,481

* This lime application is divided equally between the 10-20 cm and 20-30 cm soil horizons

Table 4. Optimal combinations of nitrogen fertilizer rates and lime application rates with corresponding Net Present Values (NPV) for the WWC rotation, when liming is restricted to surface application only.

Annual rainfall (mm)	Acidity condition	Nitrogen fertilizer	Lime application rate (t ha ⁻¹)		Nitrogen fertilizer rate (kg N ha ⁻¹)		NPV (\$ ha ⁻¹)
			Surface (year 1)	Surface maintenance (10 yearly)	Wheat	Canola	
<325	Sub-soil	Urea	13.6	-	55	52	\$5,743
		(NH ₄) ₂ SO ₄	15.9	-	41	36	\$5,159
	Top and sub-soil	Urea	15.1	-	56	54	\$5,988
		(NH ₄) ₂ SO ₄	16.6	-	45	42	\$5,467
325-450	Sub-soil	Urea	14.1	-	83	82	\$6,559
		(NH ₄) ₂ SO ₄	16.1	-	58	58	\$5,790
	Top and sub-soil	Urea	13.5	-	83	84	\$6,798
		(NH ₄) ₂ SO ₄	15.0	1.0	62	63	\$6,029
>450	Sub-soil	Urea	12.7	0.7	114	110	\$7,905
		(NH ₄) ₂ SO ₄	13.8	1.5	77	74	\$6,939
	Top and sub-soil	Urea	9.9	0.9	114	110	\$8,048
		(NH ₄) ₂ SO ₄	10.8	1.8	80	77	\$7,081

Table 5. Optimal combinations of nitrogen fertilizer rates and lime application rates with corresponding Net Present Values (NPV) for the WWL rotation, when liming is restricted to surface application only.

Annual rainfall (mm)	Acidity condition	Nitrogen fertilizer	Lime application rate (t ha ⁻¹)		Nitrogen fertilizer rate (kg N ha ⁻¹)		NPV (\$ ha ⁻¹)
			Surface (year 1)	Surface maintenance (10 yearly)	Wheat after lupin	Wheat after wheat	
<325	Sub-soil	Urea	9.8	-	28	47	\$5,869
		(NH ₄) ₂ SO ₄	10.6	-	16	35	\$5,655
	Top and sub-soil	Urea	8.9	-	28	47	\$6,014
		(NH ₄) ₂ SO ₄	9.0	-	17	36	\$5,803
325-450	Sub-soil	Urea	9.7	-	39	69	\$7,200
		(NH ₄) ₂ SO ₄	10.0	-	16	47	\$6,923
	Top and sub-soil	Urea	8.8	-	38	68	\$7,305
		(NH ₄) ₂ SO ₄	9.2	-	17	48	\$7,022
>450	Sub-soil	Urea	8.8	-	52	92	\$8,560
		(NH ₄) ₂ SO ₄	8.8	0.6	19	59	\$8,189
	Top and sub-soil	Urea	9.1	0.5	54	94	\$8,669
		(NH ₄) ₂ SO ₄	9.3	0.8	21	60	\$8,289

Table 6. Sensitivity of results to prices of urea and lime, for WWL rotation in 325-450 mm rainfall zone, with an acidic sub-soil, when liming is restricted to surface application only and the nitrogen fertilizer source is urea.

Change in urea price (%)	Change in lime price (%)	Optimal initial lime rate (constrained to surface liming) (t ha ⁻¹)	Optimal nitrogen rate for wheat after lupin (kg N ha ⁻¹)	Optimal nitrogen rate for wheat after wheat (kg N ha ⁻¹)	Reduction in NPV if initial lime rate is 2 t ha ⁻¹ (%)	Increase in NPV if sub-surface liming allowed (%)
-30	-30	10.9	59	89	8.1	4.7
-30	Base	9.9	57	89	7.7	4.9
-30	+30	8.5	58	88	7.3	5.1
Base	-30	10.4	39	69	7.5	4.8
Base	Base	9.7	39	69	7.1	5.0
Base	+30	8.0	38	69	6.6	5.2
+30	-30	10.0	21	52	6.8	4.7
+30	Base	9.4	21	51	6.3	5.0
+30	+30	7.6	20	51	5.8	5.2

Figure 1. The three initial soil profiles modeled.

Figure 2. Model structure.

Figure 3. pH response to optimal N fertilizer and lime rates in low (<325 mm) and high (>450 mm) rainfall regions, with top and sub-soil acidity, for the WWC rotation, when liming is restricted to surface application only and the nitrogen fertilizer source is urea.

Figure 4. Percentage change in Net Present Value (NPV) for alternative lime rates, relative to the optimal lime rates (14.1 t ha^{-1} for WWC, 9.7 t ha^{-1} for WWL) in the 325-450 mm rainfall region with an acidity sub-soil, when liming is restricted to surface application only and the nitrogen fertilizer source is urea.