Farming Options for Ameliorating Acidifying Soils in South - Eastern Australia: An Economic Assessment.

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Abstract

Acid and acidifying soils occur extensively in Australia. Currently, some 90 million hectares of agricultural land in Australia is considered to be acidic and around 35 million hectares are considered to be highly acidic which is both a serious agricultural and environmental problem. The nature, impact, and causes of soil acidification vary across Australia, as do farming systems and the institutional and socioeconomic issues relating to land management. In high-rainfall areas of south-eastern Australia, managing acid soils is particularly difficult in permanent pasture systems. In this paper, an economic analysis is made of the results of a long-term trial (MASTER – Managing Acid Soils Through Efficient Rotations) aimed at developing a sustainable agricultural system which can stop soil acidification and ameliorate subsurface acidity in the 500-800 mm rainfall zone . Data from four basic treatments (with and without lime) such as annual pastures, annual pastures / crop rotation, perennial pastures and perennial pastures / crop rotation were analysed. We used average crop yields and wool cuts during 1992 to 1997 and calculated gross margins for the options. Using discounted cash flows, the economic benefits of the different treatments were examined. The implications for farmers in those regions are identified and explored.

Key Words: soil acidity/pH/amelioration/farming/rotations/gross margin/stocking rates

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Introduction

Acid and acidifying soils occur extensively in Australia specially in high rainfall crop or crop/pastures areas. Soil acidification is an insidious process that develops under most modern agricultural systems particularly where chemical fertilisers are used and nitrogen fixing species of pastures and crops are grown. In general, the greater the productivity, the greater the potential soil acidification rate. Use of modern production technologies have contributed much in accelerating the rate of soil acidification process over the rate from natural processes.

A survey conducted by Helyar et al (1990) showed that in NSW about 13.5 million hectares of lands have a soil pH less than 5.0 which includes 8.5 million hectares of agricultural land. They also found that over 40% of the agricultural land that received more than 500 mm average rainfalls was affected by low pH. The extent of the problem is of such concern to the NSW government that an Acid Soil Action Program has been established funded by Treasury to the extent of $7 m until June 2000.

With the decrease in soil pH, i.e with the increase in soil acidity, imbalances in macro and micro nutrient elements occur which seriously affects plant growth. It can cause aluminium (Al) and manganese (Mn) toxicities while inducing deficiencies of calcium (Ca), magnesium (Mg) and molybdenum (Mo). Phosphate availability in acid soils is low and added phosphate is rapidly rendered unavailable. Imbalances in soil nutrients can cause restricted root growth, adversely affect legume nodulation and can reduce the over summer survival of rhizobia. Limited root growth restricts production of some crops and reduces animal production from perennial pastures (eg lucernes). The management alternatives available to farmers include the application of lime, the selection of more acid tolerant crop and pasture species, and a reduction in stocking and fertiliser rates to reduce the rate of acidification.

Soil acidity can be regarded as a natural resource stock which must be managed through time. As pointed out by McInerney (1976) the key principle in a managing natural resource stock such as the level of soil acidity is to equate the marginal benefits from running down soil pH in the current period with the marginal user cost, MUC, of this strategy. The MUC includes the value of production lost in future time periods from the reduction in pH in the current period. There is a dynamic element to this problem in that production in the current period is affected by current pH and in turn has an impact on next period's pH. Ignoring this marginal user cost leads to higher rates of soil acidification than is optimal.

There is ongoing debate about whether the acidification of soils induced by agriculture is a cause of other forms of degradation with off-site effects. At least in theory the lower productivity and persistence of deep rooted perennial plant species on acid soils means that there is greater opportunity for invasion of weed species and erosion and greater accessions to the watertable which may result in salinity problems elsewhere in the catchment. These arguments are explained in more detail in Cregan and Scott (1998) who agreed with other research concluding that 'The water cycle is a unifying concept which links many of the significant land degradation/agricultural productivity problems…'.

There appears to be some correlation between the Statistical Local Areas (SLA's) in NSW that experience the most severe soil acidity with those that experience the most severe dryland salinity (Gretton and Salma, 1996, p.C12). However experimental evidence confirming this relationship and allowing the joint modelling of these two soil health issues seems to be lacking. The LWRRDC and other agencies are presently funding research in the Boorowa and Lodden-Campaspe catchments that may help redress this lack of data.

Acidification of the topsoil eventually leads to acidification in the subsoil. The development of toxicities in the subsoil causes the loss of deeprooted perennial plant species. While it is technically possible to ameliorate acidity in the topsoil by incorporating lime, ameliorating acidity in the subsoil is a much more difficult problem although Cregan and Scott (1998) refer to a claim by Sumner (1995) that the technology now exists to ameliorate acidity in the subsoil. If acidity in the subsoil can only be reversed at very slow natural rates then from an economic viewpoint subsoil acidity may best be regarded as a non-renewable resource and the likelihood of associated externalities is higher.

The objective of our research, which is part of the Acid Soil Action Program, is to evaluate alternative strategies for the management of soil acidity in crop and pasture farming systems. We recognise that farmers treat soil acidity as an input and choose to manage it in a way that enhances their income from farming as they do in the management of other inputs. The optimal level of soil acidity will be influenced by product prices and the cost of amelioration.

Our hypothesis is that it will be profitable to use lime to manipulate soil acidity in cropping and improved pasture situations. In extensive grazing on native pastures however, stocking rate and fertiliser strategies that slow down the rate of soil acidification may be more profitable than the use of lime. If it is not profitable to arrest soil acidification at some level and if research can demonstrate that there are significant externalities associated with soil acidification, it is important to consider the impacts of farmers' decisions about soil acidification on the rest of the community and a possible role for government.

The objectives of this paper are more modest. After describing more fully the biological processes associated with soil acidification, previous economic analyses of the issue are reviewed with particular attention being paid to the 'Lime-it' model developed by Hochman, Godyn and Scott (1989) and to the recent research of Trapnell (1998). The final section of the paper is more forward looking in that it describes an approach to the dynamic modelling of soil acidification that we would like to apply as our research progresses.

The main part of the paper reports a discounted cash flow analysis of experimental data from MASTER (Management of Acid Soils Through Efficient Rotations) trial being undertaken near Wagga in which lime is being applied in a range of cropping and pasture scenarios. We recognise that this analysis provides a very incomplete response to hypotheses about lime use on farms. However our results are consistent with current expectations about scenarios in which lime use is likely to be profitable and this process of analysis has provided significant guidance to developing the economic and biological relationships required by the more sophisticated optimal control approach that we hope to apply as our research progresses. Our findings here will also provide a benchmark for comparison with the results from dynamic modelling and hence an indication of the value of these more expensive modelling approaches.

The Process and Consequences of Soil Acidification

The current acidity status of soils in Australia is the result of a combination of a natural process and agricultural impact. Natural processes operate on a near geological time scale. The impact of modern agricultural practices is much more rapid. For example, in some situations 20-30 years of agricultural practices have resulted in a similar amount of acidification as in tens of thousands of years of natural processes.

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Soil acidity is determined largely by soil composition and the ion exchange and hydrolysis reactions associated with the various soil components (Thomas and Hargrove,1984). It is measured in terms of pH scale which is the negative logarithm of hydrogen ion concentration. The pH scale ranges from 1 to 14 and 7 is considered as the neutral value[1]. All values less than 7 are considered acid, however most plant species are not affected until soil pH_{Ca} drops below about 5.2 (Cregan and Scott, 1998) at which point the performance of crop and pasture systems deteriorates because of aluminium, manganese and hydrogen ion toxicities and deficiencies of molybdenum, calcium, magnesium and phosphorus (Cregan and Scott, 1998).

Soil becomes acid through three mechanisms involving the nitrogen and organic carbon cycles. Cregan and Scott (1998) identify these mechanisms as the use of legumes, the harvesting or removal of agricultural outputs and wastes and the use of acidifying fertilisers. Legumes often accumulate most of their N in NO_3^--N form through symbiotic N_2 fixation, which is the major source of plant N. The leaching of NO_3^--N is a dominant factor resulting in a permanent decrease in base saturation and an increase in the exchange acidity of the soil. In southern Australia decreases in soil pH of about 1 unit in 50 years have been recorded under annual subterranean clover/volunteer grass pastures that are fertilised with superphosphate (Williams, 1980) and under similar pastures in rotation with cereal crops (Helyar, 1991). About

[1] It is important to note that in logarithmic scale a soil solution with pH 5.2 has ten times more hydrogen ion than that with pH 6.2, and soils of pH 4.2 are 100 times more hydrogen ion in the solution than that of pH 6.2 soil. The pH measured in 0.01M calcium chloride is very close to the natural pH of the soil, and is often recommended because it reduces variability due to seasonal factors (Horsnell, 1985). pH ($CaCl_2$) is generally 0.6-0.8 unit lower than pH(H_2O) at the same soil liquid ratio (White, 1997).

half this acidification had been attributed to nitrate leaching following increases in N_2 fixation by subterranean clover in response to superphosphate (Helyar and Porter, 1989). Evidence is now accumulating that the nitrate leached under the pasture can be reduced by half or possibly more by establishing perennial grasses with the subterranean clover (Ridley *et al.* 1990).

Minimising acid production in the organic carbon cycle can be achieved by reducing the export from and accumulation in the ecosystem of organic anions. This involves reducing accumulation of the surface litter layer, soil organic matter, and of live plant material, as well as reducing exports of organic anions in products and waste products (Helyar, 1991) by feeding conserved forages on paddocks from which the forage was removed, for example. Removal of product low in organic anions such as starch dominated cereal grain is less acidifying than removal of products high in organic anions such as lucerne hay.

Nitrate fertilisers are neutral N sources, whereas ammonium fertilisers are more acidifying N sources if NO_3^- leaching occurs. However, nitrate fertilisers are far more costly per unit of N reflecting higher mining, transport and manufacturing costs. Ideally, if N supply matches plant plus microbial demand, the NO_3^- "opening windows" for nitrate leaching would be closed, or at least the size of the windows would be minimised.

Other strategies to manage soil acidification include the adoption in cropping rotations of acid tolerant species and the incorporation of lime at sowing time. In pasture situations, one approach is to apply lime to the surface and to wait for lime dissolution and movement downward into the soil profile before a response by the pasture can be expected. However, the poor returns from livestock enterprises at present make this a high cost approach to the amelioration of acidity. Consequently there is interest in using an opportunistic cropping strategy to incorporate lime economically in farming systems dominated by livestock enterprises. The problem of managing acidity on non-arable lands remains.

A Review of Economic Analyses of Soil Acidification

In Australia, there is extensive biological research into soil acidification but economics research into this issue has been relatively neglected. Some effort has been devoted to estimating the extent and cost of soil acidity within Australian agriculture. An estimate of the extent of acid soils in each State is presented in Table 1.

Table 1 Extent of Acid Soils in Australia (million hectares)

States	Highly Acidic	Moderate Acidity	Slightly Acidity
	(pHca <4.8)	(pHca <4.9 - 5.5)	(pHca <5.6 - 6.0)
New South Wales	13.5	5.7	5.1
Victoria	3.0	5.6	5.5
Western Australia	4.7	4.7	n/a
South Australia	2.8	n/a	n/a
Queensland	8.4	32.0	n/a
Tasmania	1.0	n/a	n/a

(Source: AACM 1995)

According to the LWRRDC report (1998) there may be 24m ha of agricultural land in Australia with a pH of less than 4.8 and production losses may be in the order of $134m. According to the LWRRDC report, the area of acidic agricultural land in NSW and the value of lost production was estimated to be 9.5m ha and more than $100m[2]. The 1986-87 land degradation study in NSW reported that about one third of SLAs concentrated in the southeast of the State but extending to the Riverina suffered from severe induced soil acidity and that there were a large number of SLA's where soil acidity was likely to become severe (Gretton and Salma, 1996, p. C10). There seems to be general agreement that soil acidity is both one of the most important soil health issues and that it is becoming more severe particularly in sandy soils, high rainfall areas and farming systems based on ammonium fertilisers (LWRRDC, 1998, p.8).

These studies can be categorised as attempts to measure the annual cost of soil acidity in terms of production foregone. Gretton and Salma (1996) and Reeves et al. (1998) have good discussions on the limitations of these types of studies. In particular, because they lack a benefit/cost framework these cost estimates provide little guidance as to how soil acidification should be managed in the future from the viewpoint of either farmers or the community.

There have been a number of studies which have applied marginal analysis to liming strategies. Hall (1983) tried to analyse economic response to lime application by different crops and pastures such as corn, soybean and alfalfa (lucernes). He made an attempt to integrate plant response to lime curves and the corresponding production value increases. He performed marginal economic analysis for each of the crops to identify the respective economic lime rates in different states of America such as Kentucky, Virginia and Alabama. Edmeades et al (1985) conducted a study on effects of lime on pastures in northern islands of New Zealand. They mainly used pastures response curves to lime in a model to identify the economic returns from liming pastures.

In Australia, economic research has also followed this line of modelling the plant and economic response to pH. May and Godyn (1982) using marginal economic analysis found that lime application in a cropping phase was economically viable. Actual estimates of the effects of soil acidification in terms of economic losses to a farm were

[2] Note that these numbers have not been revised since the 1995 report and it is not clear what year the dollar values relate to. Note also that the LWRRDC estimates refer specifically to agricultural land which may explain why its estimates are lower than the AACM estimates.

made by Godyn et al (1987) for southern New South Wales. They performed whole farm analysis by using linear programming for three different pH levels. It was evident from their analysis that 52% reduction of net income occurred due to pH declined from 5.0 to 4.6. They also found that further decline in pH to 4.2 resulted in negative income i.e net loss for the rotations. Break-even analytical technique based on discounted cash flow was followed by Kennelly (1994) to evaluate investment in liming for cropping / grazing farming in eastern Victoria. He found it was profitable to use higher lime rates than the normal agronomic trial rates.

AACM (1995) conducted benefit/cost analyses of the use of lime to ameliorate acidity in eight regions in Australia vulnerable to production losses from induced acidification. In this study (also reported in Gretton and Salma 1996, pps E18-E22) it was estimated that the rate of lime application in Australia in 1989-90 was about 0.5 million tonnes and that this was about a quarter of what was required to maintain current pH levels. A further 2.3 m tonnes were required to ameliorate the 1.5 m ha where soil pH was less than 4.5. AACM found that generally lime application only had favourable IRRs in cropping situations.

Other noteworthy research is that by Hochman, Godyn and Scott (1989) and by Trapnell (1998). Hochman, Godyn and Scott (1989) developed a model called "Lime-It" which used marginal analysis to identify the economically optimal lime rate for subterranean clover pastures. Trapnell (1998) in his masters thesis gave an indication of the benefits of lime in north-eastern Victoria and south-eastern New South Wales. These two studies are reviewed in more detail below to determine the extent to which they are dynamic in nature and hence appropriately account for the user cost of running down soil pH in the current period.

Both Lime-it and Trapnell's research are simulation models rather than optimising models. They compare alternative management strategies for lime use on the basis of standard investment criteria such as the sum of discounted returns over an investment period. The original version of Lime-it was envisioned as a decision aid for the amount of lime to be used in pasture systems. The biological relationships are represented explicitly within the model as soil, pasture and livestock modules. There is also an economics module which Trapnell (1989) was somewhat critical of. He suggested that there may have been some double counting of the opportunity cost of capital invested in livestock and was also critical of some confusion in the way information about profitability and financing requirements were presented.

Trapnell used a spreadsheet based budgeting approach for three soil types and a range of cropping/pasture rotations. The biological relationships were represented as fixed coefficients in the budgets as opposed to being explicitly incorporated in the model as for Lime-it. These coefficients were derived from research by Slattery and Coventry (1993).

Both these approaches have some dynamic capabilities in the sense that they maximise discounted returns over an investment period where the returns in any time period are a function of soil pH which in turn responds to management options over time. However as simulation models they do not have an optimising capability and hence only by simulating a large number of scenarios varying by lime use, pH and crop and pasture rotation, is it possible to identify strategies approaching optimality.

The Analysis of the MASTER Trial Data

The objective of the Managing Acid Soils Through Efficient Rotations (MASTER) trial is to develop a sustainable agricultural system which can stop soil acidification and ameliorate subsurface acidity in the 500-800 mm rainfall zone. As alluded to in the Introduction and made explicit in the next section, the analysis of dynamic processes such as soil acidification requires knowledge of response relationships such as that between crop and pasture production and soil acidity and on transformation functions which indicate how soil acidity is transformed through time by crop, pasture and liming strategies.

The trial has been conducted since 1992 on the property 'Brooklyn', at Book Book about 50 kilometres southeast of Wagga Wagga. A key feature of this site is that the pH of the soil was near 4.0 to a depth of 20 cm and below 4.5 to about 30 cm depth. However, there was considerable variation in the sub-surface soil acidity below 20 cm at the site. The annual rainfall is 650 mm.

There were 8 treatments replicated in 80 plots. The plot size was 1350 square meters. The treatment details are described as follows:

1. PP- : Perennial pastures - phalaris, cocksfoot, lucerne, subterranean clover (no lime)

2. PP/C- : Perennial pastures/crops - perennial ryegrass, lucernes, subterranean clover (three years) followed by a crop rotation of oats/triticale, lupins/peas and wheat (3 years)(no lime).

3. AP- : Annual pasture - annual ryegrass, subterranean clover (1 year) (no lime)

4. AP/C- : Annual pasture - subterranean clover (1 year) / wheat (1 year) (no lime)

5. PP+ : Same as 1 but limed at six yearly intervals to achieve an average pH_{ca} of 5.5.

6. PP/C+ : Same as 2 but limed to pH_{ca} 5.5 as in treatment 5.

7. AP+ : Same as 3 but limed to pH_{ca} 5.5 as in treatment 5.

8. AP/C+ : Same as 4 but limed to pH_{ca} 5.5 as in treatment 5.

Treatments 5, 6, 7, 8 were limed in 1992 with the initial lime rate of 3.7 t/ha to increase pH_{Ca} from 4.0 to 5.5 at 0 - 10 cm. The maintenance lime rate of 2.7 t/ha was applied every six years according to the phase of the rotation to maintain an average pH_{Ca} (0 - 10 cm) of 5.5. The cost of lime cost was $ 65/t including spreading. Lime was incorporated in the first year of the trial but maintenance dressings were topdressed on pasture in phase one of each rotation.

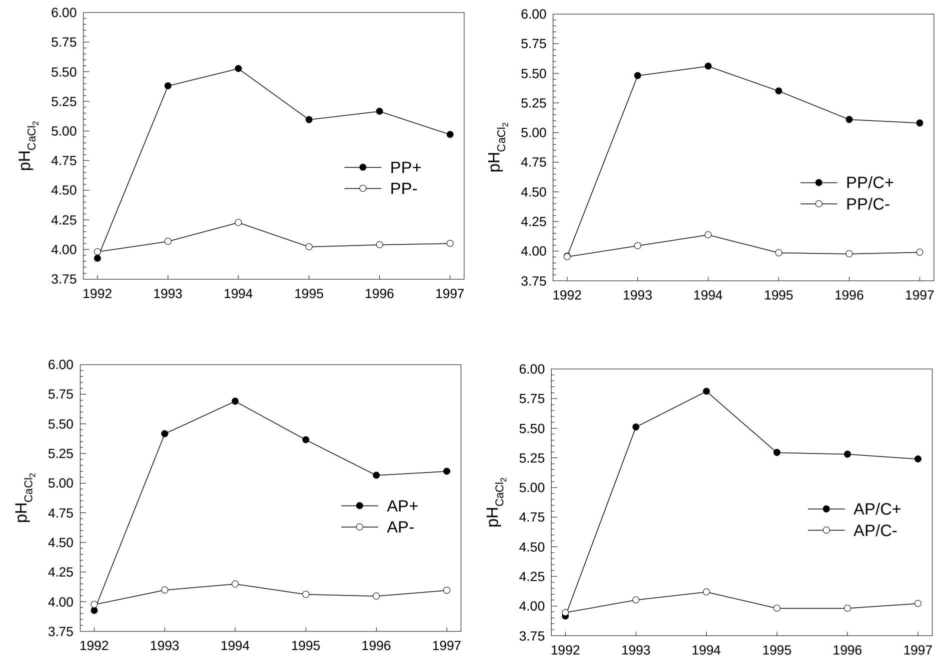

Fig. 1 Average pH at 0-10 cm for each treatment from 1992 to 1997. For limed treatments, data were extracted from those plots in phase 1 in 1992 only.

For all limed treatments, pH at 0-10 cm reached a peak of up to 5.75 in the second year after liming, then decreased gradually (Fig. 1) as acids were added to the soil by the production process and lime moved down to the subsoil. The amount of lime required to maintain pH at 5.5 has been around 450 kg $CaCO_3$/ha/year of which about 150 kg/ha/year has been accounted for by increases in pH in the 10-20 cm layer through leaching and about 300 kg/ha/year has been consumed in neutralising acids as they were added. For unlimed treatments, pH fluctuated around 4.0, however, the acids moved further down the soil profile and acidified the subsoil, which is more difficult to ameliorate.

In many respects it is much too early to analyse the MASTER trial. The trial has only been going for six years during which time there have been variations in seasonal conditions. Hence it has not been possible statistically estimate the response and transformation functions referred to above that are not 'contaminated' by seasonal conditions and the initial peculiarities of the Book Book site. Our approach was to use the treatment means from the trial for those crops which have more than 5 years' data, like wheat and oats, and to ask research and extension officers familiar with the trial and with farming systems in the area to estimate average yields for crops like lupins, peas and triticale, for which only a couple of years' data are available. The yields and stocking rates are presented in Table 2. Stocking rates were managed to maintain a wool cut of 3.35kg/dse of 19 micron clean wool. Crop yields and stocking rates were higher for limed treatments as expected. Stocking rates for PP/C treatments were lower because no stock were run during pasture establishment from break of season to September each year for year 1 pasture.

Clearly this approach is less than ideal. With more trial data we would expect to be able to identify a relationship in which plant and animal production declined with soil pH although it should also be noted that pH (at top soil) is an indicator rather than an absolute measure of soil acidity. As the soil becomes more acid throughout the soil profile, the top soil pH may change little and yet production may continue to decline.

An important consequence of having to average yields in this way is that the limited capabilities of spreadsheets in modelling the dynamic relationship between yield and pH through time are lost. Another drawback of this spreadsheet modelling approach is that there are constraints on the number of management options that can be investigated. In particular our analysis below is constrained to an evaluation of strategies that maintain soil pH at a level of 5.5. The optimal level of pH is likely to vary through time and space.

Table 2 Crop yield (t/ha) and the stocking rate (DSE/ha) used in the analysis

Treatment	Wheat	Triticale	Lupins	Stocking rate
AP -	-	-	-	11.7
AP +	-	-	-	14.6
AP/C) -	1.49	-	-	11.7
AP/C +	3.06	-	-	14.2
PP -	-	-	-	11.8
PP +	-	-	-	14.9
PP/C -	1.46	2.34	1.05	10.5
PP/C +	2.88	3.60	1.50	13.6

where - = no lime and + = lime

Some important assumptions made and sources of data used in the analysis include:

- Crop prices (on farm) used were wheat \$155/t, triticale \$150/t, lupins \$200/t;
- Wool cut was 3.35 kg/dse (clean wool) for all treatments, and price for wool was \$7.85/kg (19 micron clean wool);
- Crop productions costs were derived from the Southern NSW Winter Crop Farm Budget Handbook 1998. Particular costs included extra costs for phosphorus (15kg P/ha/yr), molybdenum (50g Mo/ha/yr) and red-legged earth mite control spray for all treatments. Sheep production costs were obtained from the NSW Wool and Sheepmeat Farm Budget Handbook, 1998;
- Perennial pastures in PP/C rotation were re-established every three years;
- Discount rate was 8% per annum

Partial budgeting (gross margin) analysis was carried out for an eighteen year period to compare the alternative management strategies. The series of net present values (NPVs) from this analysis have been shown in Table 3. Moreover sensitivity analyses were also done with respect to prices, discount rates, crop yields and wool cuts and the results have been summarised in Table 4. One comparison is with and without lime for the four farming systems. Another approach is to use the annual pasture no lime strategy as a ‘control’ being the most common farming system at present, and compare the other strategies with it. Both approaches can be followed in Tables 3 and 4.

Table 3 Total discounted gross margins ($/ha, over 18-year period)

	Total gross margin	Gain from AP (no lime)
AP -	901	-
AP +	835	-66
AP/C -	122	-779
AP/C +	998	96
PP -	830	-71
PP +	917	16
PP/C -	483	-418
PP/C +	1148	246

** *Oats and peas were grown in place of triticale and lupins in some years in this rotation but the gross margin was considerably lower with these species.*

Where **-** = no lime and + = lime

Bearing in mind the qualifications we have already expressed concerning the nature of the data and the method of analysis, the results above suggest that it does not make sense to apply lime in annual pasture grazing systems. Nor would there seem to be much to gain from moving to a perennial pasture grazing system particularly if lime is not applied. There do however appear to be reasonable returns from a farming system based on a perennial pasture crop rotation with regular application of lime to maintain pH at around 5.5. Hence an interesting hypothesis to test in an optimal control framework is that what we might call a high input farming system in which one dimension of sustainability is maintained by the application of lime, is more profitable than a low input system in which soil acidification gradually intensifies. We also need to test whether our finding that it is not profitable to topdress annual pastures with lime, which is consistent with current expectations, still holds when the dynamic nature of soil acidification is properly accounted for.

Sensitivity analysis was done to show the impact of changes in the prices of wheat and wool as well as the discount rate. Assuming annual pasture (no lime) i.e. AP- is the most common practice followed by the farmers, our attempt is to show the difference with lime use for annual pasture with lime (AP+), annual pasture and crop with lime (AP/C+), perennial pastures with lime (PP+) and perennial pastures/crops with lime (PP/C+). Table 4 shows that a wheat price increase makes the AP/C+ more competitive than the PPC+ because in AP/C+ system wheat is grown in every alternative year whereas it is grown once in every six years in PP/C+ systems. PPC+ is more competitive than the APC+ with lower wheat prices.

Table 4 Effect of prices and discount rates on gross margin ($/ha) over 18 years

		Change from AP-		
Wheat price (On-farm)	**AP+**	**APC+**	**PP+**	**PPC+**
$125/t	-$66	-$363	$16	$104
$135/t	-$66	-$211	$16	$152
$145/t	-$66	-$58	$16	$199
$155/t	-$66	$94	$16	$246
$165/t	-$66	$246	$16	$294
$175/t	-$66	$399	$16	$341
$185/t	-$66	$551	$16	$388

		Change from AP-		
Wool price (Clean wool)	**AP+**	**APC+**	**PP+**	**PPC+**
$4.85/kg	-$329	$548	-$277	$773
$5.85/kg	-$241	$397	-$180	$598
$6.85/kg	-$154	$245	-$82	$422
$7.85/kg	-$66	$94	$16	$246
$8.85/kg	$21	-$57	$114	$71
$9.85/kg	$108	-$209	$212	-$105
$10.85/kg	$196	-$360	$310	-$281

		Change from AP-		
Discount rate (Per annum)	**AP+**	**APC+**	**PP+**	**PPC+**
2%	-$9	$189	$117	$372
4%	-$34	$150	$75	$351
6%	-$52	$119	$42	$280
8%	-$66	$94	$16	$246
10%	-$78	$74	-$4	$219
12%	-$86	$57	-$21	$196
14%	-$94	$43	-$34	$177

It is evident from Table 4 that pasture/crop rotations are more competitive than the pastures when wool prices are low or wheat prices are high. PP/C+ rotations gives higher returns than the AP/C+ rotations in all situations except when wheat price is very high. Perennial pastures systems are always more competitive than the annual pasture systems with the variations in wool price.

Table 4 also reveals that the ranking of management systems is not sensitive to the choice of discount rate although at high discount rates the use of lime in purely pasture based systems is not profitable.

An Optimal Control Approach to the Management of Soil Acidity

The management of soil acidity through time has the dynamic features of many natural resource issues that make dynamic programming or optimal control the methodology most suitable to identifying the optimal management strategy. Following from work by Kennedy (1986, 1988) there has been growing interest in the application of dynamic programming and optimal control theory to natural resource issues in Australia (Cacho (1998), Jones and Medd (1997), Greiner (1998), Farquharson and Mullen (1998), Wang and Hacker (1997))[3].

As pointed out by McInerney (1976) the key principle in managing a natural resource stock such as the level of soil acidity is equate the marginal benefits from running down soil pH in the current period with the marginal user cost of this strategy which includes the value of production lost in future time periods from the reduction in pH. Modelling approaches that ignore dynamic effects recommend higher rates of resource exploitation than is optimal. Dynamic programming meets this principle by maximising a measure of wealth over time while accounting for the feedback through time between soil acidity and technology or management strategy.

As we have seen the management of acid soils involves a sequence of decisions over many years or stages, made annually say, about crop, pasture, fertiliser and liming options. These options are referred to as control or decision variables. From the farmer's viewpoint the goal is identify a strategy that maximises net farm income over a planning horizon which in the case of acid soils might be a period of twenty to thirty years. If there are contemporaneous or intertemporal externalities associated with soil acidification then there is an interest in community as well as private welfare and the planning horizon may be even longer.

At any stage the system can be described in terms of several state variables. One state variable is the phase of the cropping/pasture rotation. Of greater interest is the state of the natural resource under consideration, in this case, soil acidity. As mentioned above while pH in the topsoil may be considered a renewable resource in that it is technically and perhaps economically feasible to restore pH by liming, pH in subsoil is, with present technology, a much more intractable problem which may result in intertemporal externalities.

The returns at each stage depend on decisions about crop, pasture, fertiliser and liming options as well as the condition of the system which is affected by the values of the state variables. The key element of a dynamic resource problem is that decisions about the control variables also have an impact on the level of the state variables in the next stage through what are referred to as state transformation functions.

A Model of Acid Soil Management in a Pasture Scenario

Up to this point we have spoken on very general terms of the dynamic nature of the management of acid soils. The intention in this section is develop a dynamic programming formulation of the management of acid soils in a pasture situation. The model will be formulated using general rather than specific functional relationships. The development of specific functional relationships is a significant step in the research process requiring the analysis of experimental data from trials such as the MASTER trial described above.

[3] This project is related to an important project, partly funded by the MRC, being undertaken by Garry Stoneham and Mark Eigenram, DNRE, Victoria, Randall Jones, Weeds CRC, Orange and Ian Johnson, consultant, Armidale which is an analysis of sustainability in pasture systems.

The farmer's objective is to maximise the discounted value of a stream of net income over say 20 years by his choice of when to apply lime. The farmer's profit function, or the stage return function, is defined as:

$\pi = \rho ME_t - \sigma u_t - k - C$

Where ρ is the return per megajoule of metabolisable energy, ME, (determined from a linear programming model such as PRISM), u_t is the rate of lime applied, σ is the per unit (kg) cost of lime, *k* is the application cost of lime (unrelated to volume) and *C* is the variable costs of production unrelated to lime application. *ME* is influenced not only by seasonal conditions but also by soil fertility, particularly soil pH, through pasture composition.

The recursive equation for the dynamic programming model of the soil acidity problem is:

$$V_t\left(pH_t^U, pH_t^L\right) = \max_{u_t}\left[\pi\left(pH_t^U, pH_t^L, u_t\right) + \beta V_{t+1}\left(pH_{t+1}^U, pH_{t+1}^L\right)\right]$$

The control variable, amount of lime application, is represented by the variable *u*. This variable can take values between 0 and 5t/ha[4]. This is the typical formulation of a dynamic programming problem. The right hand side consists of two parts, a terminal value, V_{t+1}, and the stage returns in the current period, π. The problem is solved recursively by going to the last year of the observation period, t+1, and estimating the terminal value and then choosing the value of *u* that maximises the stage return in t and working back through the problem.

There are two state variables to account for soil acidity. Soil pH in the topsoil is represented by $pH^U{}_t$. Soil pH in the subsoil is represented by $pH^L{}_t$. The general transformation functions are given below. Topsoil pH is determined by previous pH, land use, x_t, and lime application. Some agricultural systems will have a grater level of annual pH loss than others. It is expected that separate runs of the model will be made for specific production systems such as the four examined in the MASTER trial.

Subsoil pH is principally determined by previous subsoil pH, topsoil pH (through leaching), land use, x_t, and to a much lesser extent lime rate in the topsoil. As already mentioned subsoil pH can be regarded as a non-renewable resource and we are interested in the impact on the system of imposing a threshold below which subsoil pH is not allowed to fall.

$pH^U{}_{t+1} = f(pH^U{}_t, x_t, u_t)$
$pH^L{}_{t+1} = f(pH^L{}_t, pH^U{}_t, x_t, u_t)$

The stage return function, π(.), is a function of the two state variables and lime decision. The stage return function represents the annual gross margin from grazing livestock on a perennial pasture system, which is estimated as $/Mj ME. The ME response function is determined by the two state variables, $pH^U{}_t$ directly affecting annual ME, and $pH^L{}_t$ affecting pasture composition and therefore indirectly ME

[4] At this rate of fine lime (98% $CaCo_3$) soil pH may be increased from say 4 to 6.5.

production. The lime decision, u_t, does not have a direct effect on annual ME production (it works through the state values) but increases the variable costs of production in proportion to the rate of lime applied as can be seen from the profit function. Hence in general form the response function may be written as:

$$ME_t = f(pH^L{}_t, pH^U{}_t,).$$

The terminal value, i.e. $V_{T+1}(.)$,is not zero as in many DP problems. Rather it represents some land salvage value (*SV*) which is a function of the two state variables. The salvage value might be the value of lime required to equate pH at the start and finish of the observation period or it might be the change in land values attributable to the way in which soil acidification has been managed.

$$V_{T+1} = f(pH^L{}_T, pH^U{}_T)$$

Clearly the next step in the research process is to make this general formulation of a dynamic programming problem operational. From experimental data generated by trials such as MASTER, specific functional relationships for the response and transformation functions have to be derived. We have represented these functions by single equations above but they are likely to be better represented by systems of equations some of which will be non-linear. The model underlying LIME-IT may well be a good starting point.

Conclusions

Soil acidification is arguably one of the most significant land degradation problems in Australia at present. It is associated with modern agricultural practices of high fertiliser use, improved perennial pastures, high stocking rates and extensive cropping. AACM (1995) have estimated that the amount of lime being used in Australian agriculture is too low to prevent the widening of the soil acidification problem.

Two key reasons among many as to why farmers do not adopt landcare technologies to combat problems like soil acidification are first the recommended remediation strategies are not profitable and second they lack authoritative information about the extent and consequences of the problem and proposed management strategies. The objective of our research is to address these two issues.

The management of soil acidity is a classic problem of the management of a natural resource where the use of the resource has to be allocated through time to the benefit of individual farmers and the broader community including future generations. The benefits in terms of current production from running down soil pH must be offset against lost production in the future. Soil acidification through agricultural practices, while much faster than natural processes, still occurs over a period of twenty to thirty years. This long time horizon makes management extremely difficult partly because of uncertainty about the physical parameters of the process and partly because of inherent difficulties of planning over such long periods. A particular problem is that many of the financial management tools commonly used do not adequately account for the future consequences of running down soil pH for current production. Such techniques promote a rate of land degradation higher than is optimal from the viewpoint of either the farmer or the community.

The objectives of this paper have been to describe the biological and economic nature of soil acidification with a view to identifying an appropriate dynamic modelling framework to be applied to this problem as better biological information becomes available and to report on a preliminary analysis of the MASTER trial near Wagga. With respect to the first of these objectives, an important feature of the modelling framework developed is the identification of two state variables in the form of pH in the topsoil and pH in the subsoil. While pH in the topsoil is at least technically a renewable resource, this may not be the case for pH in the subsoil under existing technology. There is a greater likelihood that contemporaneous and intertemporal externalities are associated with the acidification of the subsoil. In future modelling work we will be examining the consequences of imposing threshold values on subsoil pH in the spirit of a safe minimum standard.

With respect to the analysis of the MASTER trial, our findings were closely aligned with the expectation that liming is not a profitable option in annual pasture grazing situations but that it is profitable in more intensive farming systems based on a perennial pasture and crop rotation. The qualifications to this finding were first that at this early stage, the data from the trial were inadequate and second and more importantly, the method of analysis used was unable to capture dynamic effects between pH and production and hence was likely to be biased towards a greater rate of soil acidification than is desirable. Hence a key hypothesis to test in an optimal control framework will be the profitability of a low input extensive grazing system in which soil acidification slowly progresses relative to the more intensive perennial pasture cropping system with regular applications of lime.

Cropping is not an option in many parts of the slopes and tablelands of south east Australia. If it is not in the interests of farmers in these areas to ameliorate the rate of soil acidification using present technology then consideration needs to be given to whether this land degradation is a private matter or has broader community implications.

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