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Title

The economics of liming in arable crop rotations: analysis of the 35-year Rothamsted and Woburn liming experiments

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Short running head title

Economics of liming arable land

Abstract

Liming is a common management practice, but there exists uncertainty about the economic benefits. An economic analysis of the costs and profitability of liming arable crops was undertaken using data from the long-term liming experiment at Rothamsted and Woburn. There was a strong liming effect on gross margins, but large differences in the economic benefit between crops. For some crops (such as spring barley) liming greatly improved the gross margin, while for spring oats liming provided very little increase. Most economic benefit was achieved with the high lime treatment, but the cumulative discounted cash flow indicated that it took approximately 20 years before a distinct difference developed between the lime treatments. Therefore, lime should be considered a capital investment and economic evaluation undertaken over a long period. Liming rate increased the net present value expressed as an annual equivalent (*NPVa*). An additional £436 ha^{-1} yr^{-1} at Rothamsted and £208 ha^{-1} yr^{-1} at Woburn of profit was gained from the adoption of the most profitable liming treatments over not liming. Sensitivity analysis indicated that total liming costs had a weak effect on *NPVa*, but crop price had a strong effect. The economic performance of liming differed between sites and was higher at Rothamsted than at Woburn, mostly because of soil differences. Liming greatly improves economic returns of most arable crops, but the magnitude of the long-term economic benefit depends upon the sequence of crops within a given rotation.

Keywords: lime, profitability, economic analysis, soil acidity, long-term experiment

Introduction

Liming is a common management solution for acidic soils. The addition of limestone is a simple and long-established practice which improves soil fertility. Soil acidification is a major global form of soil degradation (FAO, 2015). Indeed, acidic soils cause several environmental problems such as increased NO_3^- leaching and heavy metals such as Al^{3+} (Conyers et al., 1991). Therefore, agricultural potential is greatly reduced by acidic soils. For crop production soil acidity is a threat to both profitability and sustainability. The correction of soil acidity through the application of lime as a means of soil management has major economic implications and this interaction is the main concern of this study.

With regard to liming in the UK, there are two important issues to consider: (i) the area of acidic soils and (ii) the amount of lime applied. Recent survey data in the UK indicate that 41% of arable soils have a soil pH (water) < 6.5 and 57% of grassland soils have a pH < 6 (PAAG, 2019). Over the past 40 years there has been a dramatic decrease in the production and the use of agricultural limestone. Since 2000 there was <2m tonnes of limestone produced annually, whereas in the 1980s and early 1990s it was between 3-4 m tonnes (Idoine et al., 2016), suggesting that too little lime is applied in the UK.

Most previous studies on the economics of liming in agriculture have had relatively short-term assumptions, e.g. a 4-year term or less (Bongiovanni and Lowenberg-DeBoer, 2000; Kaitibie et al., 2002) and rotations up to 5 years (Mills et al., 2020). The slow effect of liming on soil fertility suggests that it is necessary to evaluate the economic benefit over the long-term (Kalkhoran et al., 2020). Indeed, it is worth asking how long does an application of lime provide a beneficial yield response and what are the economic trade-offs? The 'time' factor is more important than ever given the capital and operational cost of crop production. Related to this is the issue of risk. The two predominant risks in agriculture and crop production are environmental or climatic risks, associated with crop yield responses, and the output price related to production costs (Kimura et al., 2010). Good agronomy will include management decisions that attempt to concurrently reduce risk and maximise profit. This requires a better understanding of how liming interacts with production and economics under uncertainty over the long-term.

Land use between farms varies in type and composition, and there are many different crop rotations in practice. Thus, it is reasonable to ask, how do the economics of liming differ according to farm type? In addition, there are significant differences in yield response to lime between crops. For example, spring barley and winter wheat have a positive yield response to lime, while spring oats and potatoes do not respond to lime (Holland et al., 2019). The differences between crop yield responses, their acidification rates, and economics of production represent a complex and dynamic inter-temporal decision problem for identifying the most suitable liming strategy over a whole crop rotation. Alternatively, as a simplification for a given crop rotation, what is the economic optimum rate of lime?

The overall aim of this paper is to quantify the economics of the long-term liming experiment at Rothamsted and Woburn in order to better understand the profitability of liming arable crops. This was done through an analysis of the historic dataset from the experiment that covered a period of 35 years from 1962-1996 (Holland et al., 2019). The experimental data permits determination of the economics of different liming rates under a permanent long-term crop rotation on two contrasting soils. A sensitivity analysis was undertaken to evaluate the economic sensitivity of different liming scenarios to product prices and lime input costs. The objectives were: (*i*) to determine the costs and income of arable crops under different liming treatments, (*ii*) to undertake an investment appraisal of different liming rates for a long-term arable crop rotation, and (*iii*) to evaluate the effect of changes in liming costs and crop price on the economic viability of liming.

Materials and Methods

The economics of liming arable crops is discussed using the soil pH and crop production data from the long-term (from 1962 to 1996) liming experiment at Rothamsted and Woburn. The Rothamsted site is located in Sawyers field at Rothamsted Research, Harpenden, Hertfordshire, UK (51.8157 N, 0.3752 W). The soil has a silty clay loam texture and is classified as a Profundic Chromic Endostagnic Luvisol (WRB, 2006). The Woburn site is in Stackyard field, section-C, at Woburn Experimental Farm, Husborne Crawley, Bedford, UK (52.0003 N, 0.6149 W). The soil texture at Woburn is a sandy loam and is classified as an Eutric Rubic Arenosol (WRB, 2006). Further details on the soils are available for Rothamsted (Avery and Catt, 1995) and for Woburn (Catt et al., 1980). There were nine different crop types grown, including: cereals (barley, oats, triticale, wheat), break or minor crops (linseed, beans, lupins, oil seed rape) and potatoes. Conventional management practices were applied at both sites for the duration of the experiment (e-RA, 2019; Holland et al. 2019).

At each site a factorial experimental design with two randomised blocks (of 16 plots each) was used. Each plot was split into two which allowed the application of sub-plot treatments. Over the course of the experiment seven treatments were applied, including different rates of phosphorus, potassium and magnesium. For simplicity this study is focused only on the four lime (ground chalk, $CaCO_3$) treatments: control (C) plus low (L), medium (M) and high (H) rates of lime. Over the course of the experiment applications were 15 and 9 t $CaCO_3$ ha^{-1} for the L treatment, 24.5 and 25.5 for the M treatment, 52.5 and 45.5 for the H treatment for Rothamsted and Woburn, respectively. Lime was applied on similar dates at each site and was applied in six separate applications: twice in 1962 and once in 1978, 1981, 1982 and 1986. Further details of the experiment are provided in Holland et al. (2019).

Long-term economic performance

To determine the long-term economic performance, discounted cash flow methods are used as they take into account both the time value of money and the total profitability over a project's life (Malcolm et al., 2005; Nuthall, 2016). To simplify the findings, net present value as annuity (*NPVa*) of each treatment at each site is calculated, which represents the lump sum net present value expressed as an annual equivalent (Nuthall, 2016), as follows:

$$NPVa = NPV\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \quad (1)$$

where *NPV* is the net present value (£ ha^{-1}), i is the discount rate, and n is the total number of years that the *NPV* spans. *NPV* is the sum of discounted future cash flows, such that:

$$NPV = \sum_{j=1}^{n} (B_j - C_j)\left(\frac{1}{(1+i)^j}\right) \quad (2)$$

where B_j is the cash inflow in the j^{th} project year, and C_j is the cash outflow (including capital outlays on lime) in the j^{th} project year. In addition to reporting *NPVa*, the cumulative discounted annual cash flow (*C-DCF*) and individual crop gross margins for each site and lime treatment have also been calculated and reported. The $C\text{-}DCF_j$ indicates the summed cumulative series of annual discounted cash flows up to and including the j^{th} year, such that:

$$C - DCF_j = \sum_{j=1}^{j} (B_j - C_j)\left(\frac{1}{(1+i)^j}\right) \quad (3)$$

C-DCF is similar to *NPV*, but it provides insight into how the overall economic performance of a system evolves through time (especially given the repeated capital outlays as lime treatments), such that in the final years *C-DCF* is equal to *NPV* (when $j = n$). Gross margins are commonly calculated for comparing alternative farm activities (Barnard and Nix, 1979, Malcolm et al., 2005; Nuthall, 2016) and here provide insights into crop economic efficiency under alternative liming treatments.

Crop gross margins

The gross margin for each crop in every year at each site was calculated as the crop income less the variable costs (Barnard and Nix, 1979). For each liming treatment the mean crop yield (t ha^{-1}) was used and the liming treatment effect (P value) was calculated using analysis of variance (ANOVA) (Table S1 and S2) undertaken in Holland et al. (2019). The mean crop yield was multiplied by crop prices (Table 1) to determine the income and cash inflow (B_j) for a given year. The standard variable costs are given in Table 2, but for calculating crop gross margins the cost of lime was excluded. This is consistent with previous studies that treat lime as a capital investment due to its long-term effect (Lukin and Epplin, 2003). To calculate annual cash outflows (C_j), variable costs and any costs of liming, such as that of the lime, transport and spreading, were annually aggregated.

The assumptions used in this study reflect the recent state of crop profitability and costs of liming. The prices of inputs and outputs are in GB pounds sterling (£) at 2019 values and, to avoid the complications of inflation and historical differences, recent crop prices and costs of production were used across all years. These were sourced from the John Nix Pocketbook for Farm Management (49th Ed. 2019) (Redman, 2018). No allowance was made for fixed costs (including machinery depreciation) as they would be expected to be identical across all treatments on a per hectare basis. However, for potatoes other crop specific costs were included (see miscellaneous in Table 2) (Redman, 2018). For fallow years (n = 4) partial variable costs (at £50 ha^{-1}) were allocated, which represents the actual herbicide spraying costs in those years. The discount rate applied in this analysis was 3.5% as suggested by the UK government (HM Treasury, 2018).

[insert Table 1 and 2 near here]

Sensitivity analysis

Differences in the costs of lime vary between farms and depend on at least two factors: (*i*) the lime cost ex-quarry, and (*ii*) their distance from the quarry and hence the transport costs for delivery. Variation in these two factors could have major implications for the overall costs of liming and hence the long-term economic performance of liming in arable systems. The sensitivity analysis was based upon 25 lime cost scenarios, including all the combinations of five different lime costs (ex-quarry) and five different transport distances (Table 3); all costs were sourced from Redman (2018).

[insert Table 3 near here]

The price of outputs from cropping activities is a key driver of crop profitability and hence their variability determines the long-term economic benefit from a liming treatment. To undertake a sensitivity analysis for each treatment, the median crop prices in Table 1 were multiplied by 1.2, 1.1, 0.9 and 0.8 to investigate the impact of five different crop price levels on the *NPVa* of each treatment and site.

Results

The effect of liming rate on crop gross margins

The gross margins (£ ha^{-1}) were calculated for each crop at Rothamsted and Woburn over the course of the experiment, with the mean and range (i.e. minimum and maximum) shown in Table 4. Some crops, such as winter triticale, spring lupins, winter lupins, linseed, winter oilseed rape, only appeared once with a harvestable yield during the experiment. At Woburn the winter lupin crop failed in both years the crop was sown. The other crops (i.e. spring beans, spring barley, potatoes, spring oats, winter wheat) produced harvestable yields in >2 years, so the minimum and maximum gross margin are presented for these crops only. Large differences in the calculated gross margins were observed both between the crops and also between the sites. For most crops, increasing the liming rate above the control had a positive effect on crop gross margins.

[insert Table 4 near here]

At Rothamsted several crops (including spring beans, spring barley, potatoes, spring lupins and winter oilseed rape) achieved the maximum gross margin under the high lime treatment. The medium liming treatment produced the highest gross margins (or least negative) for potatoes, spring oats, winter triticale, linseed, and winter wheat, while the gross margin for winter lupins was a maximum for the low lime rate. For all crops at Rothamsted the control lime treatment had the smallest (or most negative) gross margin.

The gross margins at Woburn differed greatly from those at Rothamsted and there was greater variability between the crops. At Woburn there were only four crops (spring beans, spring barley, spring oats and winter oilseed rape) that achieved the maximum gross margin at the high lime treatment. In the medium lime treatment linseed had the highest gross margin, while for the low liming treatment it was achieved with potatoes and winter wheat. For winter triticale and spring lupins the maximum gross margin was achieved with the control, i.e. no lime treatment. However, the control had the minimum gross margin for spring beans, spring barley, potatoes, spring oats, linseed, winter oilseed rape and winter wheat. In between these extremes, winter triticale and spring lupins had the smallest gross margin for the medium lime treatment.

A comparison between the sites shows that the gross margins for most crops were higher at Rothamsted for the high and medium lime treatments than at Woburn. In contrast, at Woburn the gross margins were mostly higher under the low lime and control treatments compared to Rothamsted. Overall, there was a stronger positive liming effect on gross margins from liming on the crops at Rothamsted than at Woburn. This indicates an important interaction between site and liming. The site effect is related to soil type differences and is discussed below. Both sites had a number of negative gross margins, especially for the control treatment in some crops and all liming treatments for potatoes.

The effect of liming rate on the cumulative discounted cash flow

The discounted cash flow (£ ha^{-1}) represents a transformed annual net cash flow to account for the 'time value of money' (Barnard and Nix, 1979). To illustrate the overall monetary evolution of the lime treatments the cumulative discounted cash flow (*C-DCF*) (£ ha^{-1}) was calculated as the accrued summation of discounted annual cash flows (Eqn. 3) from each year of the experiment (Fig. 1). The main similarity between the two sites was that it took more than 20 years for large differences to emerge between low, medium and high liming rates in the *C-DCF*.

At Rothamsted the control treatment mostly had negative *C-DCF* values and by the end of the experiment was close to -£6,000 ha^{-1} (Fig 1a). By the 4th year of the experiment, the control had the lowest *C-DCF* and became negative by year 7. Overall, the high lime treatment had the highest *C-DCF*. During the first ten years there was very little difference between the three liming rates. During the middle years (10 to 25) the medium lime treatment had the most positive *C-DCF*; the low lime treatment always had a positive *C-DCF*, but remained lower than the medium and high lime treatments. It was not until 25 years after the start of the experiment and the fourth lime application that the *C-DCF* values increased greatly for all three liming rates (low, medium and high).

At Woburn there was no clear difference between any of the treatments during the first 12 years (Fig. 1b). From 12 years onwards the control treatment had negative *C-DCF* values until year 25. The control treatment then fluctuated around £0 ha^{-1} and achieved a final value of -£600 ha^{-1} at the end of the experiment. Up until year 21 there was very little difference between the low, medium or high lime treatments. The most distinct differences in *C-DCF* values emerged between year 21 and the end of the experiment. Overall, the high lime treatment had the highest *C-DCF* values, followed by the low treatment with the medium lime having the lowest.

[insert Fig. 1 near here]

The effect of liming on the net present value

The relationship between *NPVa* and the total lime applied (t ha^{-1}) illustrates the positive effect of liming (Fig. 2). At Rothamsted there is a clear curvilinear increase in *NPVa* with increasing amounts of lime applied over the 35-year experiment, albeit with diminishing marginal returns. A similar relationship can be observed at Woburn, where even a small amount of lime applied (low treatment) has a noteworthy effect on increasing the *NPVa*. The difference in long-term economic performance between the highest returning treatment, the high lime treatment, and the control is around £436 ha^{-1} yr^{-1} at Rothamsted and £208 ha^{-1} yr^{-1} at Woburn.

[insert Fig. 2 near here]

A sensitivity analysis of *NPVa* was undertaken through two generalised scenarios: where (*i*) there are five different crop prices with the same total liming costs (Fig. 3a & 3b), and (*ii*) there are five different total liming costs with the same crop price (set at 100% of the price in Table 1) (Fig. 3c & 3d).

[insert Fig. 3 near here]

In the first scenario (Fig. 3 a, b), the control treatment has a constant *NPVa* which is around -£217 ha^{-1} yr^{-1} for Rothamsted and -£32 ha^{-1} yr^{-1} for Woburn. The high lime treatment at Rothamsted maintained the highest *NPVa*, followed by the medium and the low lime treatments. Similarly, at Woburn the high lime treatment produced the highest *NPVa*, but then was followed by the low treatment and then the medium treatment. At both sites the effect of total liming costs was small but reduced the *NPVa* with increasing costs of liming. The *NPVa* values for Rothamsted were higher than for Woburn under the high and medium lime treatments, but lower for the low lime and control treatments. Overall, there was a very small effect of total liming costs on the *NPVa*, and even with very high costs of liming, *NPVa* was positive for high, medium and low lime treatments.

There was a strong effect of crop price on the *NPVa* at both sites (Fig. 3 c, d). At both sites all the treatments had a negative *NPVa* at 80% of median crop price, although the order of the treatments remained the same as in the first scenario with different total liming costs. Thus, the control treatment always had the smallest *NPVa*. The breakeven crop price for the low, medium and high lime treatments at both sites is around 90% of the median crop price. As expected, the Woburn site contrasted with Rothamsted and the *NPVa* values were lower. At Rothamsted the control lime treatment remained negative at all crop prices, whereas at Woburn it became positive at crop prices above around 105% of the median price. Interestingly, as crop prices increase, the *NPVa* for the treatments with the highest RY's increase at an increasing marginal rate, showing the multiplier effect of higher crop prices.

Fig. 3 presents a small selection of *NPVa* values for a limited number of combinations of total liming costs and crop prices. The complete set of *NPVa* values for twenty-five different total liming costs and five different crop prices combinations are presented as Supplementary information (Table S3 and S4).

Discussion

The effect of crop yield and crop rotation on the economics of liming

We have focussed on the data from the long-term liming experiments at Rothamsted and Woburn, which for this study are considered as a whole crop rotation. Consequently, the most important comparison to be made is at the long-term aggregate level between the lime treatments, especially the difference between the low, medium and high liming rates.

The relation between yield and soil pH is fundamental to understanding the economics of liming. The differences between arable crops in yield response to lime were previously published (Holland et al 2019). Fig. 4 summarises this, showing the effect of liming on yield via the relationship between relative yield (RY) and soil pH for the whole experiment. Evaluating this relationship illustrates two important points: (*i*) that there were broadly similar liming effects on RY at both sites; (*ii*) the range in RY was highly variable for the control treatment. RY varied considerably across all lime treatments (Fig. 4), although there was a tendency for it to be comparatively higher under higher soil pH. The different responses to lime were because there was a broad mixture of responsive and non-responsive crops that were tested in the experiment. The connection between the yield response for a specific crop and economic performance can be identified from the calculated mean crop gross margins (Table 4). For most arable crops increasing lime rate corresponded with much higher gross margins. An exception was for spring oats which had a very small increase in gross margin (Table 4), which is consistent with the lack of yield response to liming for spring oats (Holland et al. 2019).

[insert Fig. 4 near here]

Yield response is informative (Fig. 4), but it does not correspond directly to an economic effect (Fig. 1, 2 and 3). Thus, the yield response to lime for a given crop is only important in characterising the effect derived from liming in one year. Yield response does not indicate whether the difference in yield of a specific liming rate is positive (in economic terms) and will be maintained over the medium to long-term. The composition of crops (and their yield response) within a rotation determines whether there is an aggregated positive liming effect on crop yield. Due to the long-acting nature (i.e. slow dissolution of $CaCO_3$) of lime a long time period is required for a robust economic evaluation of liming. In this study it took more than 20 years before there was a major difference between the *C-DCF* for the different liming rates (Fig. 1). The longevity of crop yield benefits from liming varies greatly. For example, in Canada limed arable crops had increased crop yield (alfalfa, barley and wheat) for 16 to 27 years post application (Malhi et al., 1995). In comparison, Li et al. (2010) reported the payback period ranged between two and 14 years for high value crops and permanent pastures, respectively.

Liming is optimised, in economic terms, when crop yields are increased over the long-term and the difference between total future returns and the costs of application is maximised. The optimal liming strategy can only be identified by using robust economic indicators such as *NPVa*, which account for the time value of money (Malcolm et al., 2005; Nuthall, 2016). Comparison between Fig. 2 and Fig. 4 indicates such a relationship: the high lime treatment has both a high RY and the highest *NPVa*. In contrast, the control treatment mostly had the lowest crop yields (Fig. 4 and Table 6 and 7 in Holland et al. 2019) and also the lowest *NPVa* values (Fig. 2). The sites differ in the order of the medium and the low lime treatments. Nevertheless, there is clear evidence of a general correlation between the yield response to liming and *NPVa*. However, the variability in yield response to different liming rates (Fig. 4) may introduce more uncertainty in the expected economic frontier expressed as *NPVa*, especially at Woburn (Fig. 2b).

The importance of soil management and soil properties on the economics of liming

There is evidence that liming is becoming a less common soil management practice in this UK. The British Survey of Fertiliser Practice of 2019 reported that only 5.5% of arable land received limestone applications (DEFRA, 2020). This indicates that, on average, arable land receives an application of lime once every 18 years. The relatively small area that is limed suggests that crop yield potential is limited by insufficient lime. Furthermore, there are very serious economic implications of not liming crops, as observed in the negative *NPVa* for the control lime treatment (Fig. 2). The reported average lime application rates for arable crops in the 2019 British Survey of Fertiliser Practice were between 4 and 5.6 t ha^{-1} (DEFRA, 2020). These rates can be considered adequate in comparison to the rates in this study, but a focus on the lime rate is probably not appropriate given the lack of frequency in lime application outlined above. In the study lime was applied in five different years over 35 years, which on average corresponds to a frequency of once every seven years (Holland et al. 2019). Two economic indicators: *C-DCF* (Fig. 1) and *NPVa* (Fig. 2) indicate that the L, M and H liming rates were applied at a frequency which maintained positive values of farm profitability. There is most likely to be a trade-off between the lime application rate and the frequency of application. Thus, higher rates would allow for reduced frequency of application compared with low rates. Sound soil and crop management should ensure that lime is applied to match the local acidification rate and the selection of crops with a given rotation. The optimal rate and the optimal frequency will inevitably vary between soils and rotations (Goulding, 2016).

Soil properties and the specific composition of soils strongly drive the responsiveness to lime. Bailey et al. (1989) reported on the effect of soil pH and organic matter content in predicting the lime requirement, Sinclair et al. (2014) showed the importance of soil texture such that soils with a higher clay content require greater lime, and Holland et al. (2018) noted that soil properties such as organic matter and buffering capacity influenced the lime requirements. The large differences between the sites found in our work (Fig. 1, 2, 3, 4) show that the economic performance of lime is strongly influenced by soil type. For most crops in this study the gross margins at Rothamsted were higher than at Woburn (Table 4) and this could be due to differences in the soil properties. At Rothamsted there was greater clay and silt content, but a lower percentage of sand than in the Woburn soil (Holland et al. 2019). This is consistent with the findings of Liu *et al.* (2003) where they reported that the economic optimum rate of lime differed according to soil type.

The RothLime model (https://www.rothamsted.ac.uk/rothlime; Goulding et al. 1989) and the UK Nutrient Management Guide (AHDB 2017) use only two soil inputs (pH and texture) to predict the amount of lime required to raise soil pH under UK conditions (plus crop type as arable or grass and the form of lime to be used). The economic results (Fig. 1, 2 and 3) presented here were calculated using same soils data from the long-term experiment used to develop RothLime. It was therefore limited to just two different soil types (at Rothamsted and Woburn), but the economic response to liming was large for both and can be regarded as indicative for most arable soils. Thus, an economic benefit of liming is expected regardless of soil type on UK arable land. Nevertheless, there is a need for future research on the economics of liming on a wider selection of soil types.

The effect of crop price and total liming costs on the economics of liming

Increasing crop price had a very positive effect on the long-term economic performance of the liming treatments (Fig. 3). In comparison, the range of different total liming costs had little effect. This contrast between crop price (revenue) and total liming costs (capital expense) has implications for the economic risk of liming. The increased sensitivity to crop price indicates where the greatest economic risk lies from liming. The sensitivity depends on differences in the relative yields of crops, marginal economic responses and subsequent profitability, which varies between enterprises. For instance, increases in wool production was found not profitable enough to apply lime by Khairo and Norton (2010) at the given input costs and commodity prices. In contrast, it is probably better to include the higher value, pH-sensitive crops in a rotation after applying lime. However, Mills et al (2020) found that variable rate liming (i.e. precision liming as in precision fertiliser use) was only profitable where above average crop prices were received.

Additional factors which influence the economics of liming

In addition to cost and price assumptions, crop rotation and soil effects, further work is required to consider additional factors which influence the economics of liming. Four key factors include:

(i) Lime quality in terms of its the neutralising value and solubility affects the performance of different limestones (Conyers et al., 1996). Likewise, there are large differences in the elemental composition of quarried limestone material and these differences exist spatially across the UK (Chater and Williams, 1974);

(ii) Nitrogen (N) supply is a major driver of crop yield and its interaction with soil pH can influence crop responses. Does liming improve the profitability of applying N fertiliser? The importance of lime to optimise N fertiliser has been demonstrated for forage production in the US (Tumusiime et al., 2011). Furthermore, the application of lime and N fertiliser together create a challenging trade-off between reducing greenhouse gas emissions and increasing crop production (Gibbons et al., 2014);

(iii) Crop rotations should be taken into account when considering the frequency of liming. Recent work of Kalkhoran et al. (2020) indicated that the economics of liming is influenced by the inclusion of leguminous crops in rotations. In particular, how does excluding crops such as oats or potatoes, which are not responsive to lime, influence the economics of liming? Our research, covering a unique rotation, but one which includes common crops grown on arable soils, provides an indication of the long-term economic performance of liming for the UK and elsewhere.

(iv) We considered crop price risk and lime input costs (Fig. 3). However, variations in yield and how different crops respond under different climates, soil types, and soil pH could be further integrated into economic analyses through stochastic and dynamic modelling. In future work risk, as well as the already mentioned interactions, could be embedded into the decision-making process for the concurrent optimisation of liming, fertilisation and crop rotation over both the short- and long-term.

Conclusion

Gross margin analysis showed there were large differences in profitability between crops for the economic benefit from liming. For most crops there was strong correlation between the liming effect on both RY and gross margin. There was little economic benefit from liming for oats. The *C-DCF* indicated that it took around 20 years before a distinct difference emerged between the economic benefits of the three lime treatments. This confirms that liming is correctly considered as a capital cost. Liming rate increased the long-term economic performance (*NPVa*) and the high lime treatment always had the highest economic returns at both sites. The total liming costs had little influence on *NPVa*. In comparison, increasing crop price had a strong positive influence on the long-term economics of liming. Thus, high value crops are best used to achieve satisfactory economic performance for a crop rotation where lime is required. Overall, the profitability at Rothamsted was higher than at Woburn, which reflects mostly the soil type and its response to lime. At both sites the economic benefit of liming over not liming (the control treatment) was large, with an additional £436 ha^{-1} yr^{-1} at Rothamsted and £208 ha^{-1} yr^{-1} at Woburn of profit to be gained from the adoption of the most profitable liming treatments. Thus, for arable crops where lime is required, the complete absence of lime is detrimental to economic performance. However, to maintain long-term profitability the frequency of lime application is more important than the actual rate of lime applied in a single given year. Evaluation of survey data on current liming practices in the UK indicates that increased frequency in the application of lime is required for the economic benefits from liming to be realised. Further work is needed to better understand the economic optimisation of lime for a greater number of scenarios on arable land elsewhere with different soils and crop rotations.

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Table captions

Table 1. Crop price for each crop type[a]

Table 2. The variable costs (seed, fertiliser, sprays and miscellaneous) (£ ha^{-1}) for each crop in the long-term experiment[a]

Table 3. Different lime cost and transport costs scenarios for the lime cost sensitivity analysis

Table 4. Mean crop gross margins[a] (£ ha^{-1}) for the four liming treatments (control, low, medium and high) with range and the number of years successfully grown in the long-term liming experiment at Rothamsted and Woburn[b]

[Table 1]

Crop	**Crop price (£ t^{-1})**
Spring beans	185
Spring barley	157
Potatoes	145
Spring oats	140
Winter Triticale	145
Winter & Spring lupins	275
Linseed	380
Winter oilseed rape	335
Winter wheat	162

[a] Source: Redman (2018)

[Table 2]

Crop	Seed (£ ha^{-1})	Fertiliser (£ ha^{-1})	Sprays (£ ha^{-1})	Misc.[b] (£ ha^{-1})	Total variable costs (£ ha^{-1})
Spring beans	90	49	128		267
Spring barley	63	95	149		307
Potatoes	949	279	770	2993	4991
Spring oats	67	87	94		248
Winter Triticale	57	139	80		276
Winter & Spring lupins	130	60	80		270
Linseed	90	59	64		213
Winter oilseed rape	55	173	230		458
Winter wheat	65	225	260		550
Fallow			50		50

[a] Data source: Redman (2018)

[b] Miscellaneous includes casual labour, sundry items and contracting operations such as destoning and ridging

[Table 3]

Lime cost (£ t^{-1})	Distance (miles)	Transport cost (£ t^{-1})	Total cost[a] (£ t^{-1})
2.6	25	5.6	13.1
10	50	11.2	26.1
15[b]	75	16.8	36.7
20	100	22.4	47.3
26.5	200	44.8	76.2

[a] The total cost includes the cost of spreading at £4.9 t^{-1} ha^{-1}

[b] Median costs of lime inputs and transport costs used in the base analysis of long-term economic performance

[Table 4]

Crop	No. years grown	Rothamsted Control (£ ha^{-1})	Rothamsted Low (£ ha^{-1})	Rothamsted Medium (£ ha^{-1})	Rothamsted High (£ ha^{-1})	Woburn Control (£ ha^{-1})	Woburn Low (£ ha^{-1})	Woburn Medium (£ ha^{-1})	Woburn High (£ ha^{-1})
Spring beans	4	-85 (-256; 75)	95 (-101; 212)	160 (-75; 268)	167 (-8; 295)	11 (-234; 177)	69 (-154; 173)	61 (-82; 177)	93 (-27; 244)
Spring barley	9	-157 (-307; 203)	316 (59; 646)	432 (264; 872)	450 (255; 913)	185 (-185; 527)	411 (269; 698)	475 (337; 863)	502 (359; 863)
Potatoes	3	-1603 (-1646; -1536)	-772 (-1211; -395)	-590 (-1102; -32)	-733 (-1373; -18)	-917 (-2396; 751)	-197 (-1337; 1984)	-536 (-1485; 983)	-578 (-1439; 664)
Spring oats	4	97 (-49; 220)	135 (-41; 250)	154 (-65; -32)	131 (-55; 253)	85 (-37; 301)	114 (11; 284)	113 (8; 270)	120 (10; 256)
Winter Triticale	1	629	884	923	913	704	700	674	697
Spring lupins	1	231	500	519	583	269	200	173	176
Winter lupins[c]	1	-166	332	173	118 (-270; 118)	-	-	-	-
Linseed	1	-213 (-213; 231)	809	840	798	285 (269; 285)	836	840	726
Winter oilseed rape	1	8	339	252	400	-69	353	420	443

Winter wheat	2	-269	674	791	784	-126	736	653	656
		(-432; -106)	(553; 795)	(707; 874)	(720; 848)	(-325; 74)	(710; 762)	(644; 662)	(637; 675)

[a] Mean values are given on the first line; minimum and maximum are given below in parenthesises for those crops where these were calculated

[b] These gross margins are calculated using the variable costs in Table 2 and the crop prices in Table 1

[c] Crop failure for winter lupins at Woburn only

Figure captions

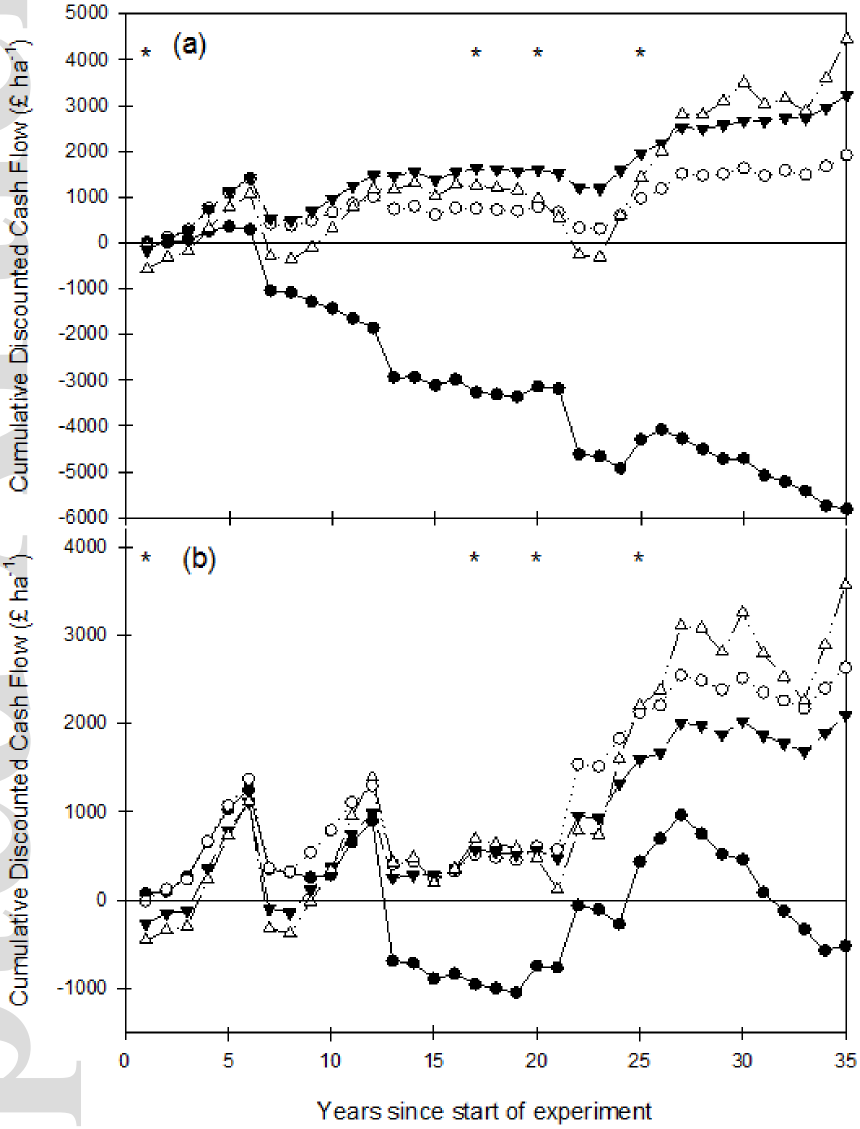
Fig. 1. Cumulative discounted cash flow (*C-DCF*) (£ ha^{-1}) over the duration of the long-term liming experiment for four liming rates (control ●, low ○, medium ▼, high △) at (a) Rothamsted and (b) Woburn. NB. Each time when lime was applied is indicated along the top of each figure with an *. The discounted cash flow data is based on a lime price of £15 t^{-1}, lime spreading at £4.9 t^{-1} and transport costs of £16.8 t^{-1} (equates to around 75 miles) (Redman 2018)

Fig 2. The annualised net present value (*NPVa*) (£ ha^{-1} yr^{-1}) at four different total amounts of lime applied (t ha^{-1}) at Rothamsted (●) and Woburn (○) over 35 years at median total liming costs and median crop price

Fig 3. Net present value (*NPVa*) (£ ha^{-1} yr^{-1}) of the liming treatments (control (●), low (○), medium (▼), high (△) at five different total liming costs (Table 3) and a constant crop price (100%) for (a) Rothamsted and (b) Woburn; and with median total liming cost and five crop prices (80%, 90%, 100%, 110%, 120%) for (c) Rothamsted and (d) Woburn

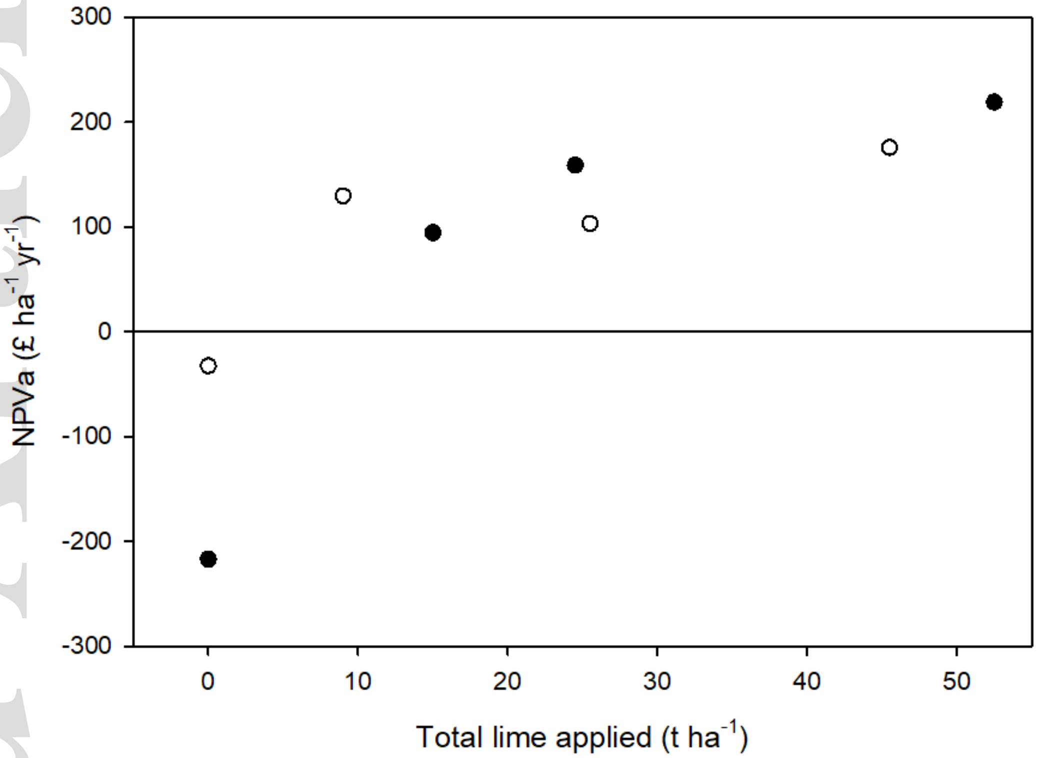
Fig. 4. Relationship between crop relative yield (RY) and soil pH (water) for four liming treatments (control ●, low ○, medium ▼, high △) at (a) Rothamsted and (b) Woburn. The RY was based on the crop yields (t ha^{-1}) given in Table 6 and 7 of Holland et al. (2019) and was calculated from the yield of a given treatment divided by the maximum yield for that crop and year

[Fig. 1]

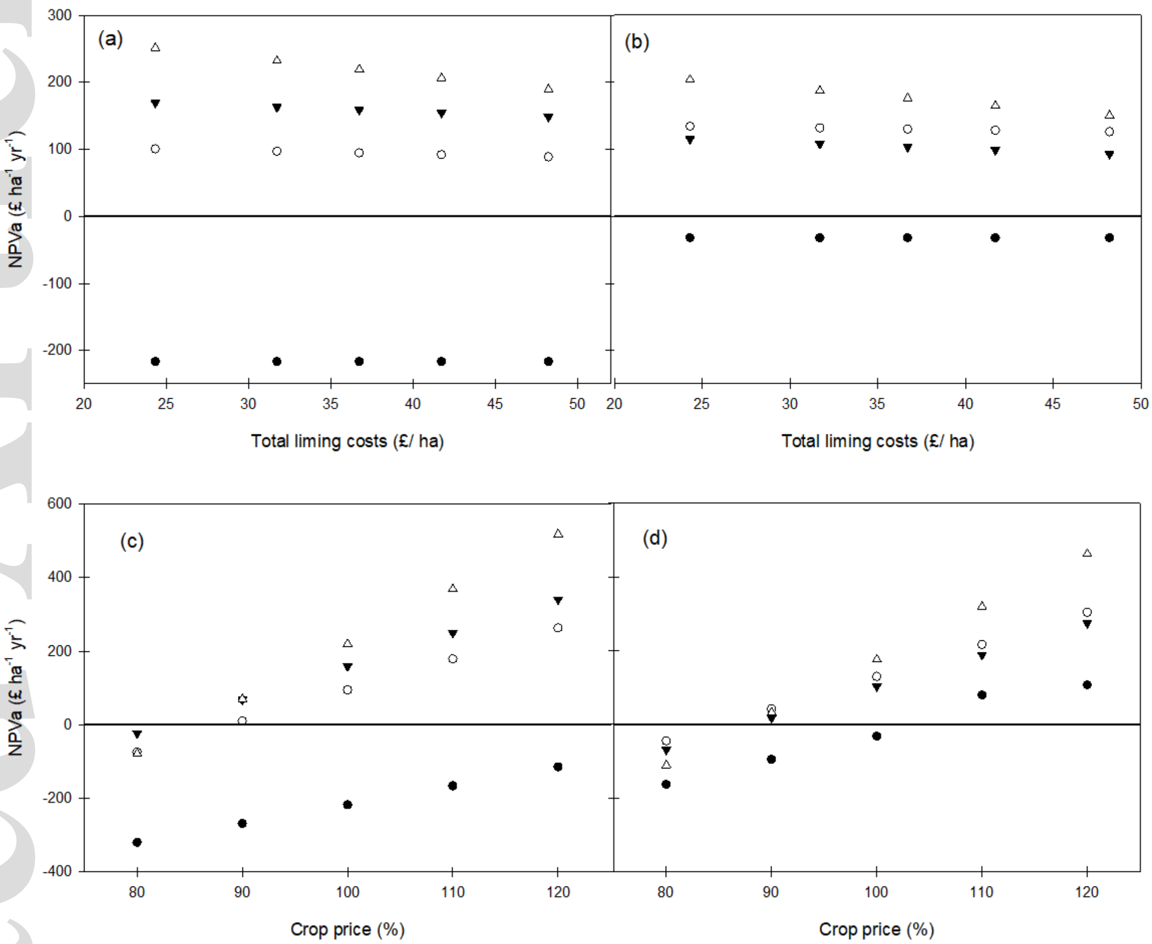


(a)
(b)
Cumulative Discounted Cash Flow (£ ha-1)
Cumulative Discounted Cash Flow (£ ha-1)
Years since start of experiment

[Fig. 2]

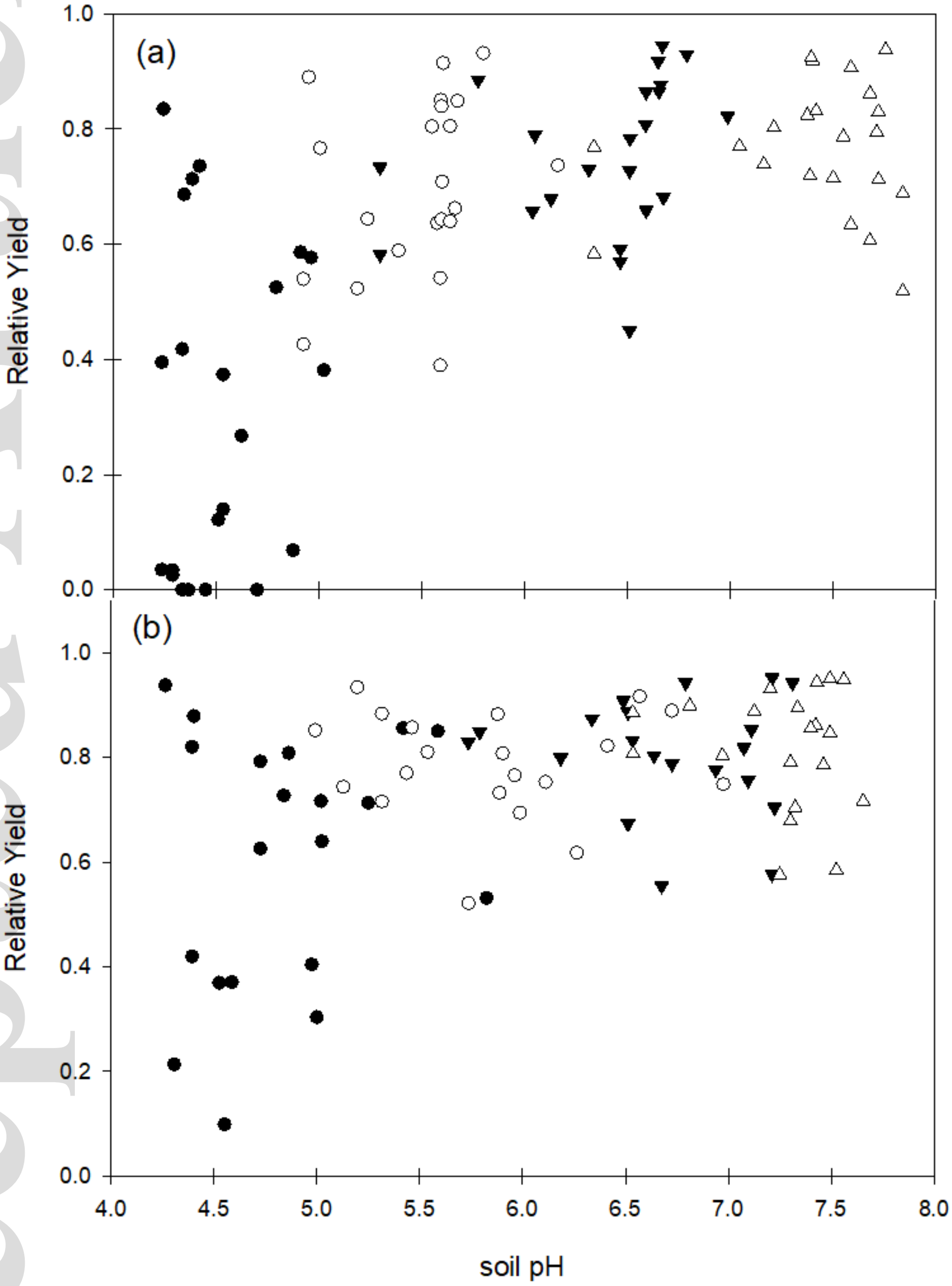

300
200
100
0
-100
-200
-300
NPVa (£ ha-1 yr-1)
0
10
20
30
40
50
Total lime applied (t ha-1)

[Fig. 3]

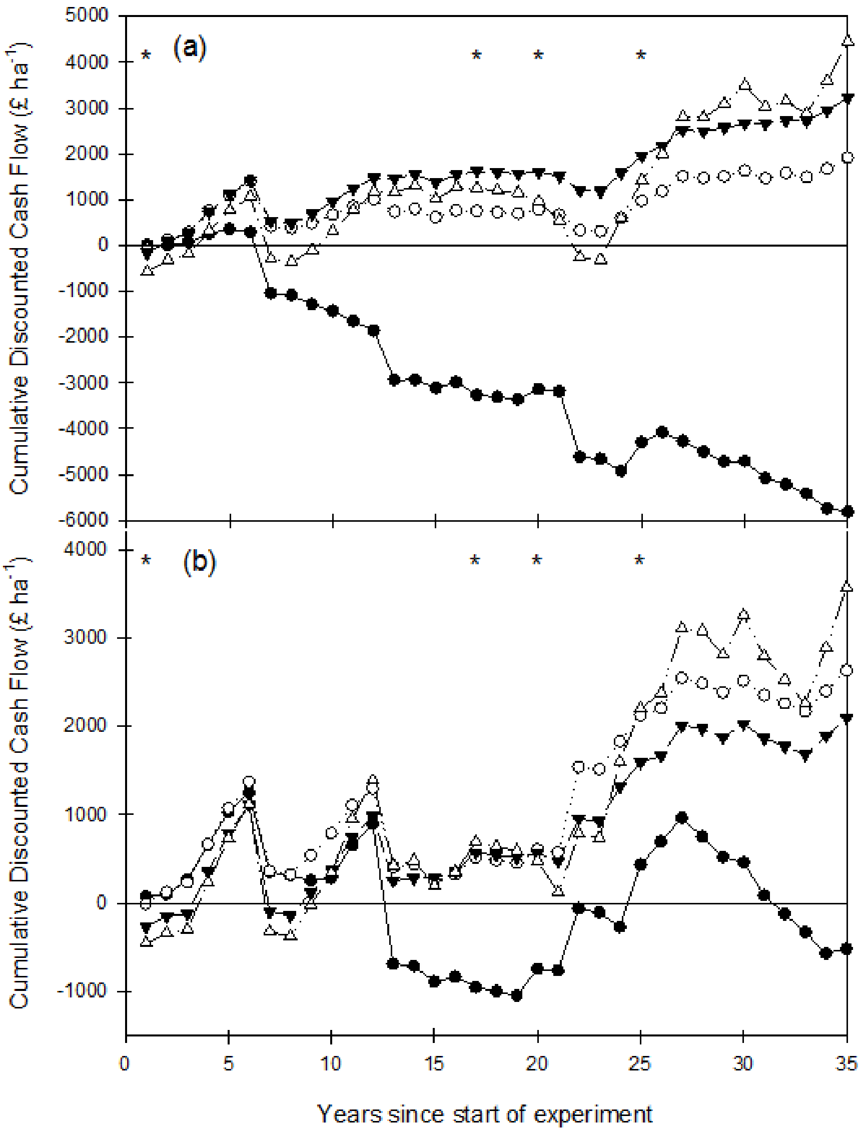


(a)
(b)
(c)
(d)
NPVa (£ ha-1 yr-1)
Total liming costs (£/ ha)
Crop price (%)
300
200
100
0
-100
-200
600
400
-400
20
25
30
35
40
45
50
80
90
100
110
120

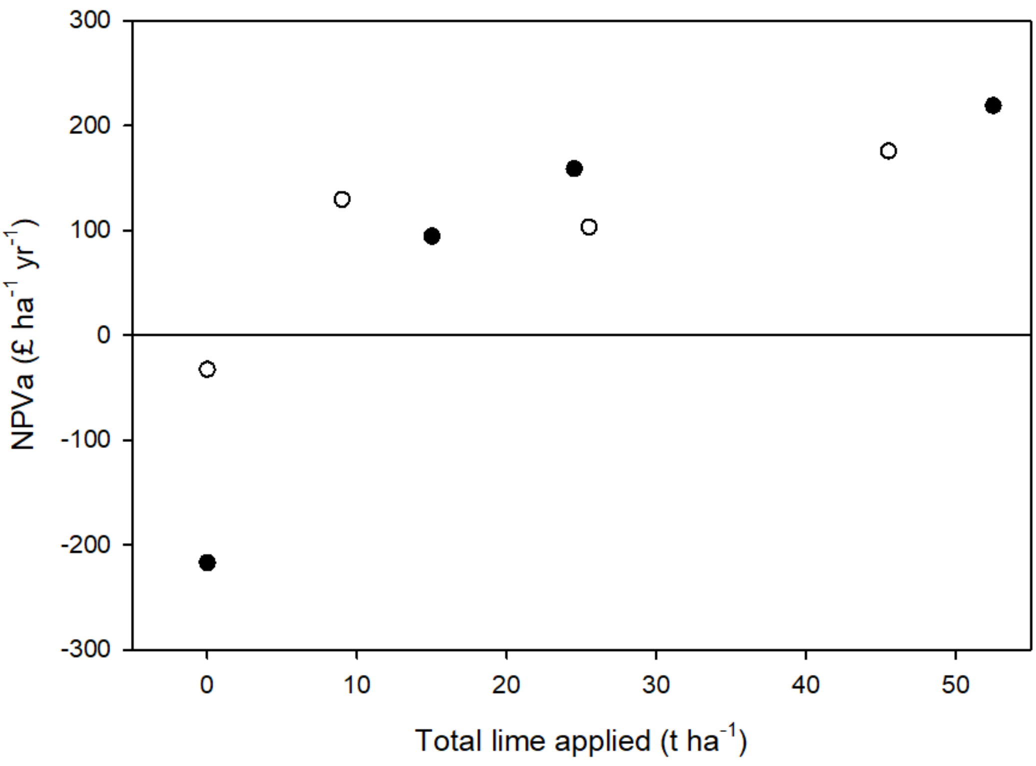
[Fig. 4]

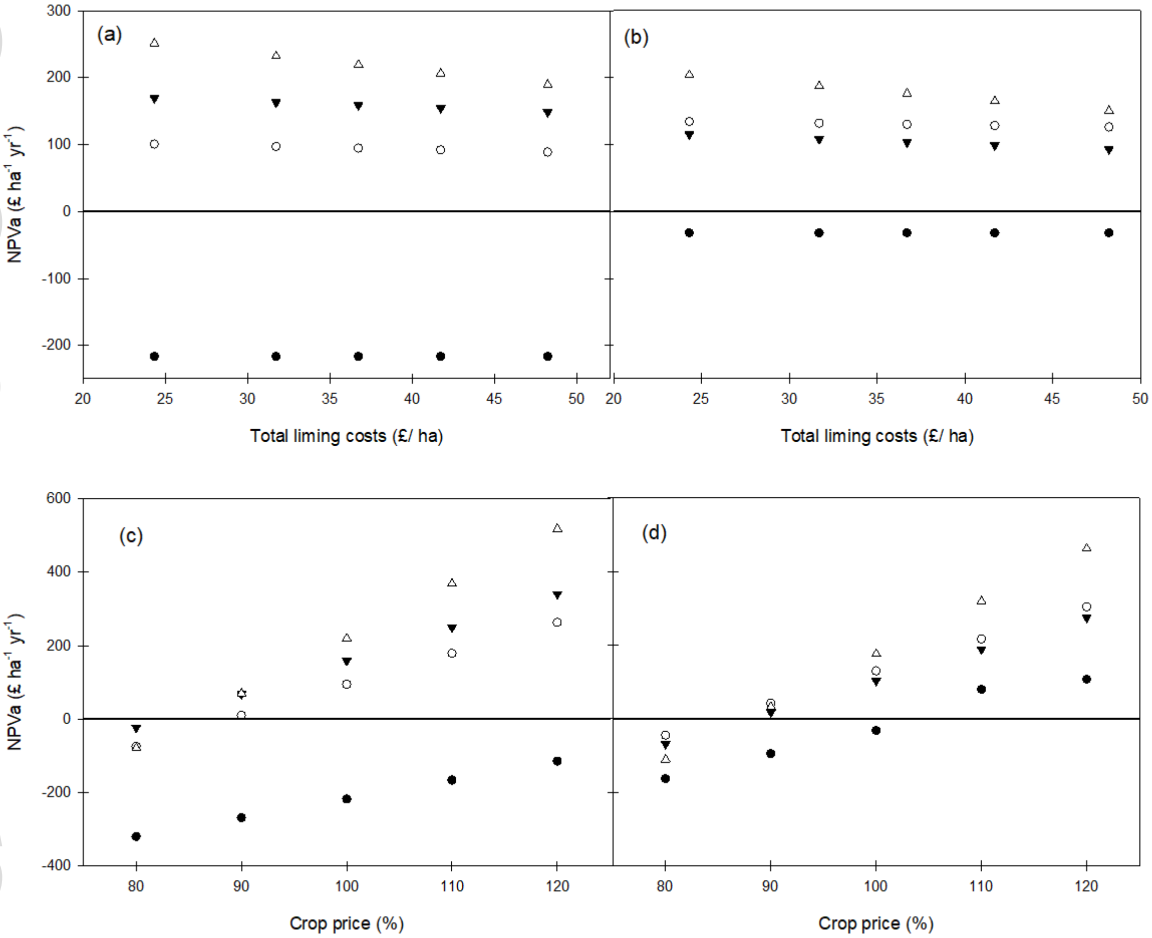


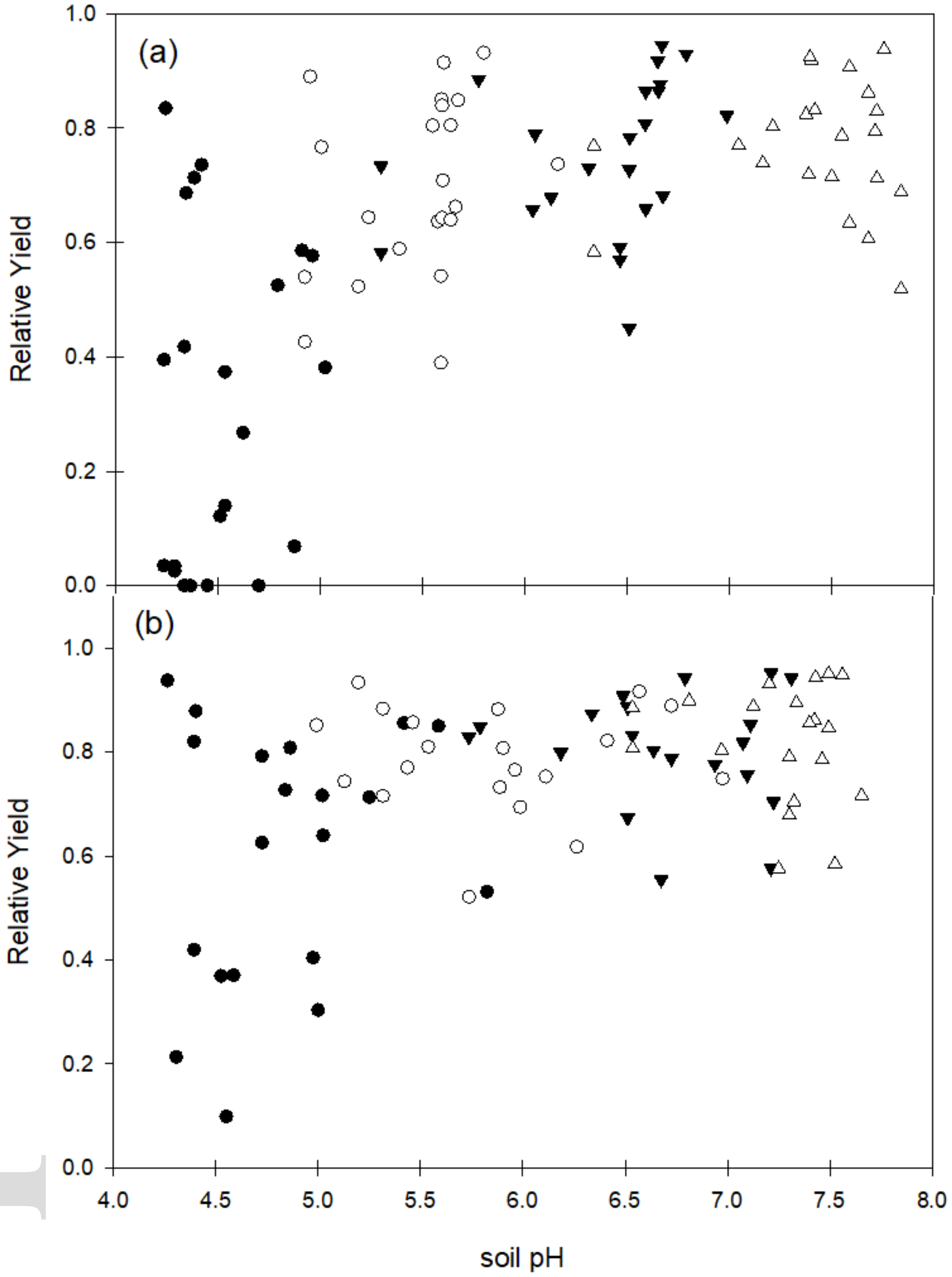
(a)
(b)
Relative Yield
Relative Yield
1.0
0.8
0.6
0.4
0.2
0.0
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
soil pH



(a)
(b)
*
Cumulative Discounted Cash Flow (£ ha^{-1})
Cumulative Discounted Cash Flow (£ ha^{-1})
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
-1000
0
5
10
15
20
25
30
35
Years since start of experiment


NPVa (£ ha-1 yr-1)
300
200
100
0
-100
-200
-300
0
10
20
30
40
50
Total lime applied (t ha-1)


(a)
(b)
(c)
(d)
NPVa (£ ha-1 yr-1)
Total liming costs (£/ ha)
Crop price (%)
300
200
100
0
-100
-200
600
400
-400
20
25
30
35
40
45
50
80
90
100
110
120


(a)
(b)
Relative Yield
Relative Yield
1.0
0.8
0.6
0.4
0.2
0.0
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
soil pH