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Predicting the lime requirement of soils under permanent grassland and arable crops

K.W.T. Goulding, S.P. McGrath & A.E. Johnston[1]

Abstract. Graphs of soil pH against time were plotted for the Park Grass Experiment at Rothamsted Experimental Station, begun in 1856, and the Long-term Liming Experiments at Rothamsted and Woburn farms, begun in 1962. These showed that the magnitude and duration of the effect of lime applications varied with soil type, initial pH, fertilizer nitrogen application, and the crop grown. Simple equations for each situation were linked to form an empirical model which, with appropriate input data for soil type, crop, and initial and target pH, predicted the lime needed to reach that pH. Model predictions compared well with estimates from a Woodruff-type buffer method. The model forms a sound basis for a more comprehensive lime requirement model covering the whole of the United Kingdom.

INTRODUCTION

LIMING soil with chalk or limestone ($CaCO_3$), quicklime (CaO), or slaked or hydrated lime ($Ca(OH)_2$) to raise its pH has been common practice in farming for centuries. Current advice offered to British farmers suggests that mineral soils should be maintained at pH values (measured in water) of 6.5 for arable crops and 6.0 for grassland (Archer, 1985). Farmers can obtain recommendations from various organizations on how much lime to apply to achieve a certain pH. Such recommendations are generally based on extraction with a neutral salt, titration, buffer solutions or the difference between exchangeable bases and the Cation Exchange Capacity (Thomas & Hargrove, 1984). However, a method or model based on estimated annual losses of calcium by leaching and the response of the soils to past lime applications would remove the need for sampling and analysis and could give a more precise lime requirement: several have been suggested (Gasser, 1973, 1985; Bolton, 1977).

Both site and management factors determine lime losses. They include soil type, crops grown, rainfall or, more particularly, through drainage, atmospheric and fertilizer inputs of nutrients and pollutants and the pH of the soil itself. The Park Grass Experiment at Rothamsted, begun in 1856 (see Warren & Johnston, 1964) and the Long-term Liming Experiments at Rothamsted and Woburn farms, begun in 1962 (see Bolton, 1977) enable changes in the soil pH to be related to these factors and permit a simple model of the loss and requirement of lime to be constructed.

The Park Grass Experiment

This experiment examines the effect of several manurial treatments on permanent grassland on the silty clay loam soil at Rothamsted. The pasture was at least 200 years old when the experiment began in 1856. Thurston *et al.* (1976) summarized the results, and Johnston *et al.* (1986) have described certain aspects of the soil's acidification. The species composition of the pasture has been altered considerably by the different treatments, and this can be seen clearly in the well-defined boundaries between plots. The site is flat and is never ploughed, so there has been little sideways movement of nutrients in drainage and no movement of soil particles caused by cultivation. A few tests of the effects of adding lime were made after 1883, and then between 1903 and 1965 lime was applied to one half of most plots at 4 t $CaCO_3$ ha^{-1} once every four years (Warren & Johnston, 1964). Since 1965 the aim has been to maintain soil pH at 5, 6 and 7, respectively, on quarter plots by periodic lime dressings, with one quarter left unlimed. Data for recent years were used to develop the model, whilst some of the earlier data were used to test it.

The Long-term Liming Experiments

These experiments were begun in 1962 on the silty clay loam soil at Rothamsted and the sandy loam soil at Woburn (Bolton, 1977). Initially four rates of lime (0, 5, 10 and 20 t $CaCO_3$ ha^{-1} at Rothamsted; 0, 5, 12, 19 t $CaCO_3$ ha^{-1} at Woburn) were tested; further smaller amounts were applied in 1978, 1982 and 1983. Effects on soil pH, the duration of the effects, and the interaction of liming and fertilizers on crop yields under an arable rotation have all been measured.

THE LIME REQUIREMENT MODEL

Bolton (1977) constructed a simple mechanistic model to predict lime losses from the Long-term Liming Experiments. He assumed that lime loss – essentially Ca loss – was a function of through drainage, anion (NO_3^-, SO_4^{2-} and Cl^-) inputs in fertilizers and from the atmosphere, temperature,

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the partial pressure of CO_2 and soil pH. From these he calculated the concentration of anions, including bicarbonate, in drainage waters and thus the Ca leached as the balancing cation. The model fitted the experimental data well but was not developed further.

The present model takes lime loss to be a function of soil type, the crop grown (if any), rainfall (which combined with soil type gives through drainage), soil pH and the amount and form of fertilizer N applied. Atmospheric deposition is an important factor in soil acidification in the natural environment. Its effects, however, and those of SO_4^{2-} and Cl^- in the fertilizers applied, were shown to be very small on fertilized agricultural soils compared with the other factors listed above, especially N fertilizers (Johnston *et al.*, 1986). Atmospheric deposition and sulphur and chloride applied in fertilizers are, therefore, not included in the present model.

The model is empirical and estimates lime requirement from field measurements of changes in pH over a set period following lime applications. Each field experiment, or set of experiments, provides a simple equation linking the change in pH with lime applications to local conditions. It thus includes the effects of the various factors that control lime loss, and their interactions. Future developments might permit the construction of a mechanistic model by isolating the effects of individual factors in the way that we attempted for soil acidification (Johnston *et al.*, 1986).

Model construction

Soil pH, in a 1:2.5 soil:water suspension, has been monitored periodically on the Park Grass and Long-term Liming Experiments. Initially, graphs of pH against time showed how quickly and by how much a certain application of lime increased pH, and for how long the effect lasted. Figure 1 shows such data for the Long-term Liming Experiments. An example of the changes in pH induced by adding lime on the Park Grass Experiment is given in Fig. 2. This shows, for plots that are limed to attain a pH of 7, the change in pH by 1984 arising from various additions of lime in 1975/6 to

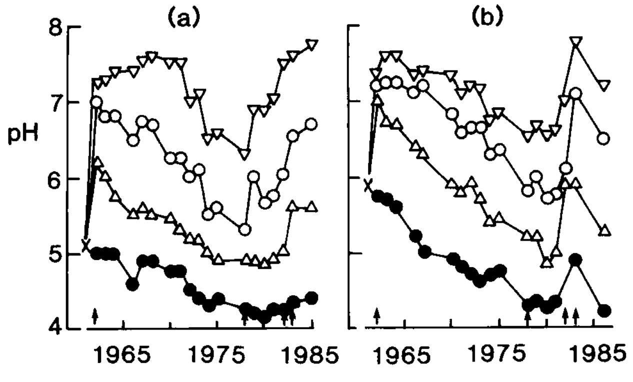

Fig. 1. The change with time of the mean pH of surface (0–23 cm) soil at (a) Rothamsted and (b) Woburn receiving 0 (●–●) and Small (△–△), Medium (○–○) and Large (▽–▽) amounts of lime at the dates indicated (↑).

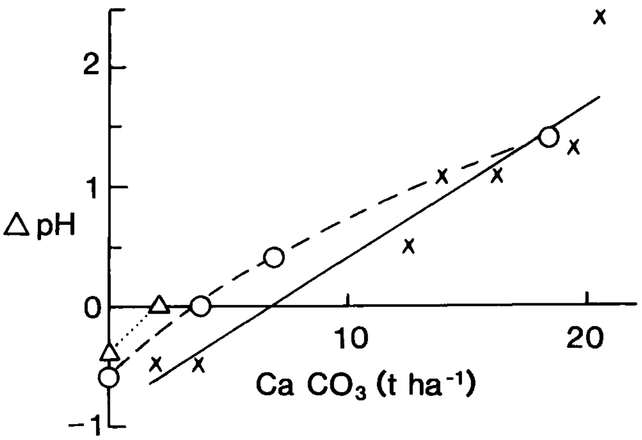

Fig. 2. The changes in pH caused by various applications of lime on the 'a' plots (target pH 7) of the Park Grass Experiment: unmanured (○), ammonium-N (×), nitrate-N and FYM (△).

soils without N and those given N in different forms: ammonium sulphate, sodium nitrate, farmyard manure (FYM); the nitrate and FYM plots have been combined. The data were separated on the basis of soil type, crop, and, where applicable, initial pH and form of N applied. Equations were then derived to describe the change in pH over a 12-year period for a given lime application. (This period was dictated by the limited pH data from Park Grass.) Some examples of the equations derived for the Park Grass plots shown in Fig. 2 are:

Unmanured and 'No N':

$$\Delta pH = 0.111L - 0.528, r = 0.96; \quad (1)$$

NH_4–N:

$$\Delta pH = 0.133L - 0.920, r = 0.96; \quad (2)$$

NO_3–N and FYM:

$$\Delta pH = 0.193L - 0.367, r = 0.67; \quad (3)$$

where ΔpH is the change in pH over the experimental period and L the lime added as t ha^{-1} $CaCO_3$.

There is some evidence of an effect from the form of N on these plots, but for target pH values of 5 and 6 on Park Grass and for both Long-term Liming Experiments there was no obvious effect of different forms of N. The data for each experiment and site have, therefore, been combined to give regression equations relating change in pH over a 12-year period to lime added as follows:

Park Grass:

$$\Delta pH = 0.060L - 0.315, r = 0.76, p < 0.001; \quad (4)$$

Long-term Liming: Rothamsted

$$\Delta pH = 0.109L - 0.690, r = 0.99, p < 0.001; \quad (5)$$

Woburn

$$\Delta pH = 0.110L - 1.160, r = 0.98, p < 0.001; \quad (6)$$

The slope of the regression equations for both Long-term Liming Experiments is the same, and the difference between them is expressed in the constant. This may indicate that the slope of such an expression reflects the close similarity in management of the sites. This is discussed further below.

These equations form the core of the model (Fig. 3). At present they permit the lime requirement to be calculated for the two experiments tested, and probably, as will be shown below, for other experiments at Rothamsted and Woburn. Working through the model, a series of choices establishes a particular combination of factors which applies in each case and, therefore, the appropriate 'ΔpH:Lime' equation. The lime requirement, in t ha^{-1} $CaCO_3$, to reach and maintain the target pH for the set time is then given.

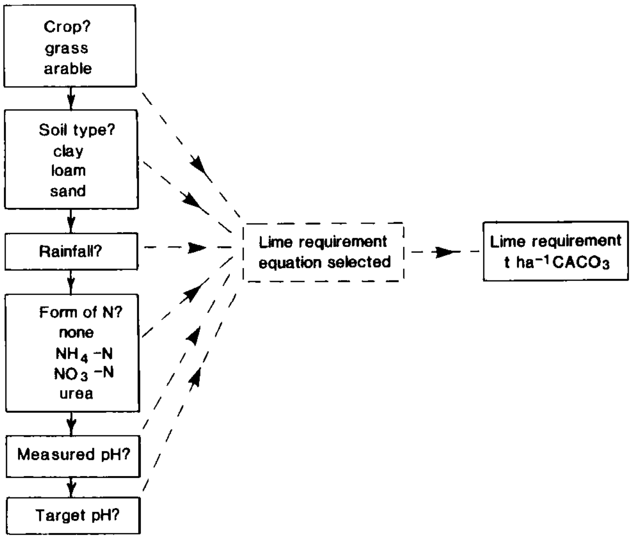

Fig. 3. The lime requirement model as currently used.

Model validation

To compare the predictions from the model with the methods currently used to assess lime requirement stored soil samples from the two experiments and other experiments at Rothamsted, with pH values of 3.9 to 7.2, were analysed using the Agricultural Development and Advisory Service's (ADAS) method for measuring lime requirement (see MAFF, 1981, 1985, 1986). This is essentially the buffer method of Woodruff (1948), in which the pH of the soil is measured after equilibration with a calcium acetate/*p*-nitrophenol/magnesium oxide buffer. The amount of lime required to adjust the soil to pH 6.0 or 6.5 is then calculated as follows:

(i) Using 'single-strength' buffer for soils of pH 5.0 to 6.4:

$$CaCO_3 \text{ required in t ha}^{-1} = (7-\text{measured pH})\times 11.2; \quad (7)$$

(ii) Using 'double-strength' buffer for soils of pH <5.0:

$$CaCO_3 \text{ required in t ha}^{-1} = (7-\text{measured pH})\times 22.4. \quad (8)$$

The lime requirements calculated from this buffer method were compared with the predictions from our model to bring the soil to the target pH.

The 'Woodruff' buffer method used by the ADAS is thought to give 'an accurate figure for the amount of calcium carbonate needed to maintain the pH of 20 cm depth of mineral soil at the appropriate level' (Archer, 1985). It is not recommended for peat, acid sulphate or upland grass soils. It is the standard method which would be used to predict lime requirement on soil such as that from Park Grass and the Long-term Liming Experiments and so is the most appropriate comparison to use for validating the model.

Comparisons of the model and ADAS buffer predictions of lime requirement are presented graphically in Fig. 4. The buffer method calculates the amount of lime required to raise the pH of arable soils to 6.5 and grassland to 6.0 (MAFF, 1986) and maintain it at about that pH for four to five years (MAFF, 1981, 1985). Our model has been 'tuned' therefore, to provide data for the same time period.

The relationships between the model and buffer calculations are approximately linear. The 1:1 line is shown, and the product moment correlation coefficients, *r*, for Woburn Long-term Liming, Park Grass and various Rothamsted arable soils are, respectively, 0.915, 0.988 and 0.958. The overall correlation coefficient is 0.950.

Agreement between the model and the buffer method is excellent. The relationship is not quite 1:1, and varies slightly with site and management practice as do the 'ΔpH:Lime' relationships. Figure 4 shows that data for the lighter textured soils (X) are all above the 1:1 line. This is probably because the model is based on measured pH changes over time, and on the sandy soil leaching losses may well have been larger than on the heavier textured soils. The buffer method does not inherently allow for subsequent leaching losses.

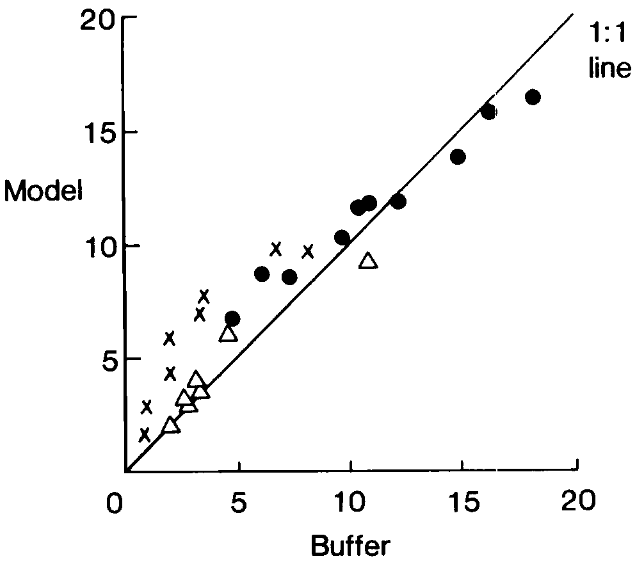

Fig. 4. Lime requirement for Woburn Long-term Liming (×), Park Grass (●) and various Rothamsted arable soils (△) predicted by the buffer method and the model; units are t $CaCO_3$ ha^{-1}.

The veracity of the model was tested further in two ways. First, the change in pH on each of the half plots on Park Grass which received lime at 4 t $CaCO_3$ ha^{-1} every four years from 1923 to 1959 was compared with the predictions from the model for the effect of this lime dressing. Over the 36-year period the mean increase predicted by the model was 0.41 pH units and the average increase measured was 0.38 pH units. Whilst the model could be used over such a period of 20 to 30 years with, perhaps, checks on soil pH at intervals, it is more likely that it would be used over a four- to eight-year period so that soil pH does not fluctuate over a wide range.

Secondly, the actual amounts of lime applied to the Woburn Market Garden Experiment (Johnston, 1975) and the Rothamsted and Woburn Reference Experiment (Williams, 1973) were compared with model predictions of the lime required to cause the pH changes observed over the earlier parts of these experiments up to about 1970. On the Market Garden Experiment, Series A plots, the model predicted that 39.5 t $CaCO_3$ ha^{-1} would cause the observed increase in pH of 0.7 units between 1944 and 1972, compared with the 37.7 t $CaCO_3$ ha^{-1} applied. On the Series B plots lime applications were uneven and not well documented. Using data available, the model predicted that 54.0 t $CaCO_3$ ha^{-1} would be required compared with the 41.3 t ha^{-1} applied. On the Reference Experiments at Rothamsted the model predicted that 20.2 t $CaCO_3$ ha^{-1} would cause the observed increase in pH of 1.2 units between 1956 and 1970, which was exactly the amount applied. At Woburn the model predicted that 15.4 t $CaCO_3$ ha^{-1} would cause the increase in pH of 1.1 units between 1960 and 1969, compared with 12.6 t ha^{-1} applied. We conclude that there is, generally, a very good agreement between the model predictions and amounts of lime actually applied.

DISCUSSION

The Woodruff buffer method has been found to be one of the most reliable methods of predicting lime-requirement in practice (Mohebbi & Mahler, 1988). Good agreement between it and the model for the various Rothamsted and Woburn soils supports the veracity of the model, as do the other tests reported which used data on past liming at Rothamsted and Woburn. However, the buffer method is not applicable to all soils (e.g. Logan & Floate, 1985) and requires ever more costly sampling and analytical services. A widely applicable model using a periodic determination of soil pH is therefore of considerable value. The present test, on a range of cropping systems but limited to two soil types, suggests that the model is worth extending to other soil types and sites.

It may be possible to derive a useful model from a limited amount of data, however. The slopes of equations (5) and (6), which describe lime loss in the Long-term Liming Experiments at Rothamsted and Woburn, respectively, were the same. This suggests that the slope of the 'ΔpH : Lime' equations may reflect the management of an experiment, i.e. crop grown and fertilizer applied. One might have hoped to see a similarity in the intercepts for the equations describing the Park Grass and Long-term Liming Experiments at Rothamsted (equations (1) to (5)), suggesting that the intercepts reflect site factors (rainfall and soil type), but this is not so. Perhaps Park Grass is too 'extreme' an experiment, having plots with pH values as acid as 3.7. More 'normal' data from farms on the same Soil Series might show similarity in intercepts and a wider applicability than just the Park Grass and Long-term Liming Experiments.

CONCLUSIONS

A model which reflects different types of soil, initial pH, through drainage and agronomic practices offers the best way forward in predicting lime requirement. The simple model presented here provides estimates of lime requirement for two experiments under grass and arable crops and on two soil types that compare well with those from a buffer method of the Woodruff type. Thus it forms a sound basis for an extended lime-requirement model.

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Soil and vegetation inter-relationships on reclaimed coal mine sites

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Abstract. A spoil and vegetation survey was conducted of five fields reclaimed from coal mine spoils seeded in different years at the Whitewood mines of south-central Alberta, Canada. It aimed to understand the causes of visibly wide variations in ground cover of the seeded species which was mainly alfalfa. Sites were initially stratified into productivity classes: A (high), B (medium), and C (low) based on the seeded species, and then sampled. Cover and dry weight declined linearly with age of reclaimed field. The spoil at class-A sites contained more clay than that of class-C sites. It also contained more moisture and a better cover. Electrical conductivity (EC) and the concentrations of soluble B, Mg, Na, and K in the spoil were significantly greater at class-C sites. Cover and dry weight of the seeded species were negatively correlated with EC, B, Mg, and Na in the spoil, thus implicating these factors in poor vegetative productivity, particularly in the dry conditions that typify this part of Alberta.

INTRODUCTION

RECLAIMING spoils after strip mining for coal in the province of Alberta, Canada, involves contouring piles of spoil into discrete fields, which are then disced and seeded to either legumes or a mixture of grasses and legumes. Alfalfa (*Medicago sativa* L.) is the most common species used. Among the species that volunteer on these spoils poplars (*Populus* spp.) and willows (*Salix* spp.) are dominant. Low fertility has been the major constraint to successful reclamation of mine spoils in this area as Danielson *et al.* (1983a) found, and which we have confirmed in small plot studies using topsoil capping media and nutrient amendments.

The object of this study was to measure those attributes of the spoil and vegetation that we believe to be important to detect relationships between spoil characteristics and measures of vegetation performance, and to examine those for the causes of poor vegetative productivity.

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MATERIALS AND METHODS

General

This study was conducted in 1979 at the Whitewood coal mine located about 70 km west of Edmonton in south-central Alberta. The overburden there consists of a surficial layer 6 to 26 m thick comprising till, sand and gravel lenses, and glacio-lacustrine materials. This overlies a bedrock of sandstones, siltstones, shale, and coal seams (Montreal Engineering Company Ltd, 1978). The original soil derived from till occurs in the Gray Wooded Soil Zone and is classified as Gray Luvisol (Canadian Soil Survey, 1978) having a strongly leached surface horizon, containing little organic matter and nutrients. The spoil at this mine varies with depth of overburden. It comprises a mixture of overburden materials. It is stony, sandy clay with no apparent internal-drainage problems. Some parting material (originating from a layer of rock within the coal seam) is still present at the top in the root zone. It is considered unsuitable for plant growth because of poor structure, excessive boron and little phosphorus (Montreal Engineering Company Ltd, 1978) but may be used to form the base of the finished contoured spoils. There is a fairly uniform distribution of coal in the root zone.