# 15. Information for agriculture from regional geochemical surveys: the example of soil pH in the Tellus and Tellus Border data

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The variation of pH of pasture soils across the Tellus and Tellus Border survey area has been analysed. Geostatistical methods allow us to quantify the uncertainty in mapped soil pH and its implications for the health and management of pasture soils. Soil pH indicates that there is a widespread requirement for liming of pasture soils across the area. We exemplify how the uncertainty in statistical predictions can be communicated to a general audience using a verbal scale.

## Introduction

Land managers and their advisers require information on soil chemistry for various important decisions. These may concern the management or control of nutrient supply, the concentration of potentially harmful elements and soil pH. The pH of soil is an important property, influencing the development and functioning of root systems, the availability of micronutrients and potential toxicity of other trace elements and the viability of the soil microflora and fauna, including important invertebrates such as earthworms which themselves affect nutrient cycling, drainage and aeration. Soils all tend to acidify because of the presence of dissolved carbon dioxide in the soil water, and agriculture may accelerate this process through nitrification by nitrogen fertilisers. For this reason land managers should pay attention to the pH of their soils and take remedial action to keep it in an appropriate range (Coulter and Lalor, 2008; Defra, 2010).

Soil pH is measured as part of regional geochemical survey, not least because of its importance in the interpretation of information on metals with pH-dependent mobility and bioavailability. In this chapter we consider whether these pH data are useful for the

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agricultural sector and how appropriate analysis can address difficulties with their use and facilitate effective communication of uncertain information. We use the Tellus and Tellus Border survey data sets to map the risk that pasture soil pH falls below target values.

## The variable and target values

Soil pH was measured on soil collected in both the Tellus and Tellus Border surveys. We do not repeat details of the surveys here, but the key information is that each soil analysis was undertaken on a subsample of material aggregated from five cores at the corners and centre of a 20 × 20 m square centred at a sample site. The sites were selected as close as possible to the nodes of a systematic grid of density one site per 2 $km^2$ in the Tellus survey and one site per 4 $km^2$ in the Tellus Border survey.

Land managers make decisions on the remediation of soil pH by comparing estimates for their land with target values. They may also consider the risk, in some settings, of creating deficiencies of certain micronutrients such as cobalt or excesses of others such as molybdenum by over-liming the soil. Target values of soil pH are published by agricultural extension organisations on the basis of field experiments. In this chapter we are concerned with pasture soils. We examine two soil pH target values. Coulter and Lalor (2008) state that pH of pasture soils should not be allowed to fall below 6.3, and propose pH 6.5 as a target pH for the manager. Defra (2010) propose pH 6.0 as a minimum for pasture soils. We examine both the 6.5 and 6.0 targets in this study. The larger target value is probably most appropriate for clover-based production systems. We also examine a minimum pH threshold for earthworms. Edwards and Lofty (1974) found that no earthworm species in the Park Grass experiment at Rothamsted could tolerate pH less than 4.0, and that other species including *Allolobophora* spp. were not found if the pH was less than 5.0. We therefore consider pH 5.0 as a target for maintaining earthworm activity.

One problem must be addressed before we can use the pasture soil thresholds. Both the Coulter and Lalor (2008) and Defra (2010) target values are based on pH measured in water. However, the Tellus and Tellus Border soil pH values are measured in 0.01 M $CaCl_2$, which is good practice in geochemistry and soil science (Schofield and Taylor, 1955). The pH of soil measured in $CaCl_2$ may be appreciably lower than the pH of the same soil measured in water. To resolve this problem for the present study we extracted topsoil pH measurements made in both water and $CaCl_2$ from soil profiles across the North of England presented by Jarvis *et al.* (1984). A linear regression line was fitted to predict pH in $CaCl_2$ from pH in water. We used 'bootstrap resampling' of the North of England data to estimate the regression, sampling with equal probability from subsets of values defined by the quartiles of the data on pH in $CaCl_2$ of the Tellus and Tellus Border soils. This was to mitigate the effect of not having an unbiased sample of data from the study region itself to estimate the regression. The regression was then used to transform the target values of 6.5 and 6.0 to values of pH in $CaCl_2$ comparable with the geochemical data. The respective target values were 5.9 ± 0.05 (95% confidence interval) and 5.4 ± 0.04. The pH data

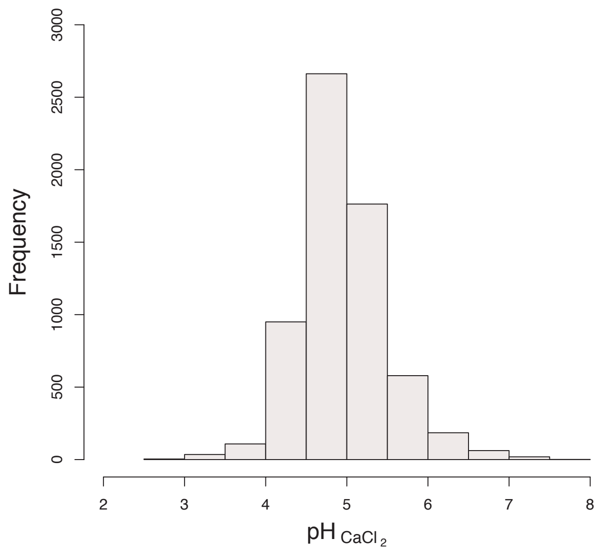


Figure 15.1. Histogram of 6368 observations of pasture soil pH in Tellus and Tellus Border data sets.

presented for the Park Grass experiment by Edwards and Lofty (1974) were measured in $CaCl_2$.

In the following two sections we outline how the variability of the soil pH data is described statistically, and how spatial prediction is then done with geostatistical procedures to map the variable across the study region.

**Table 15.1. Summary statistics of pasture soil pH measured in $CaCl_2$ in the combined Tellus and Tellus Border data sets**

| Mean | Median | Min. | Max. | Standard deviation | Skewness |
|---|---|---|---|---|---|
| 4.95 | 4.90 | 2.88 | 7.68 | 0.54 | 0.59 |

## Variability in space

We extracted the Tellus and Tellus Border pH data for all sites in CORINE Land Use class 231, Pasture (CORINE, 2006). There were 6368 observations. Figure 15.1 shows their histogram and Table 15.1 presents some summary statistics. Note that about 84% of these values were smaller than the target value of 5.9 (6.5 in water) for clover-based pasture production.

These data appear reasonably symmetrical in their distribution. However, for our analyses we require strong assumptions of normality, and so we use a method called Hermite polynomials to transform the data to a variable that can be assumed to be normal.

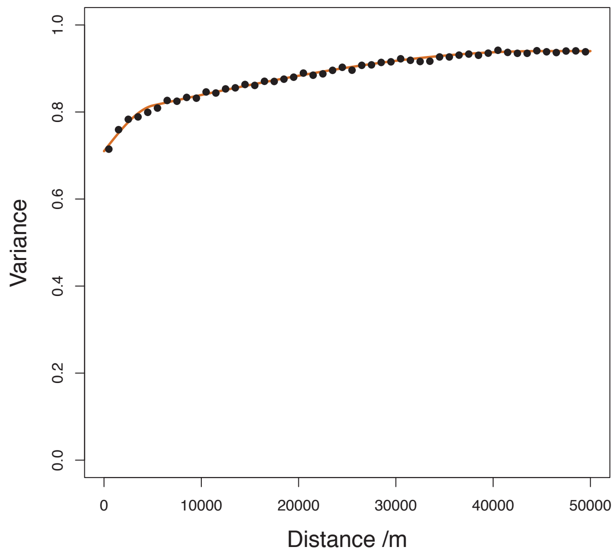


Figure 15.2 Variogram of (Hermite-transformed) soil pH in Tellus and Tellus Border data sets.

Figure 15.2 shows the variogram of the transformed variable. The variogram shows how variability of some property is spatially dependent. It is a plot of half the statistical expectation (mean) of the squared difference between two observations of the variable as a function of the distance in space between them, and as such it is a variance (Webster and Oliver, 2007). One can see in Fig. 2 how the variogram increases with distance; in general two observations close together are more similar than two that are further apart. There are two key features of the variogram in Fig. 2. First, note that there is a pronounced break of slope at a distance of about 5000 m and that the variogram flattens out at about 40,000 m. These distances represent key scales in the spatial variation of soil pH. It is likely that the longer of the two corresponds to broad variations in solid geology. The shorter scale may represent variations in the composition of superficial deposits, and climatic factors that affect soil pH. The second feature is the apparent intercept of the variogram at a value of about 0.75. Empirical variograms have an apparently non-zero intercept because of short-range variation of the variable which is not resolved at the scale of sampling. In this case the intercept, or nugget variance as it is called, will arise from factors such as differences in management between fields (some may have been limed recently at the time of sampling) and farms as well as short-range variations in topography, organic carbon content and other factors.

A farmer may well wonder whether sampling at the scales of regional geochemical surveys can provide useful information for management. The large nugget variance in the variogram in Fig. 2 puts into statistical terms the data user's intuitive sense that, even when sampling at one sample per 2 or 4 km$^2$, substantial sources of variation may not be resolved. When geostatistical predictions are made, however, they have an associated quantification of uncertainty, as described in the next section. This includes the effect of

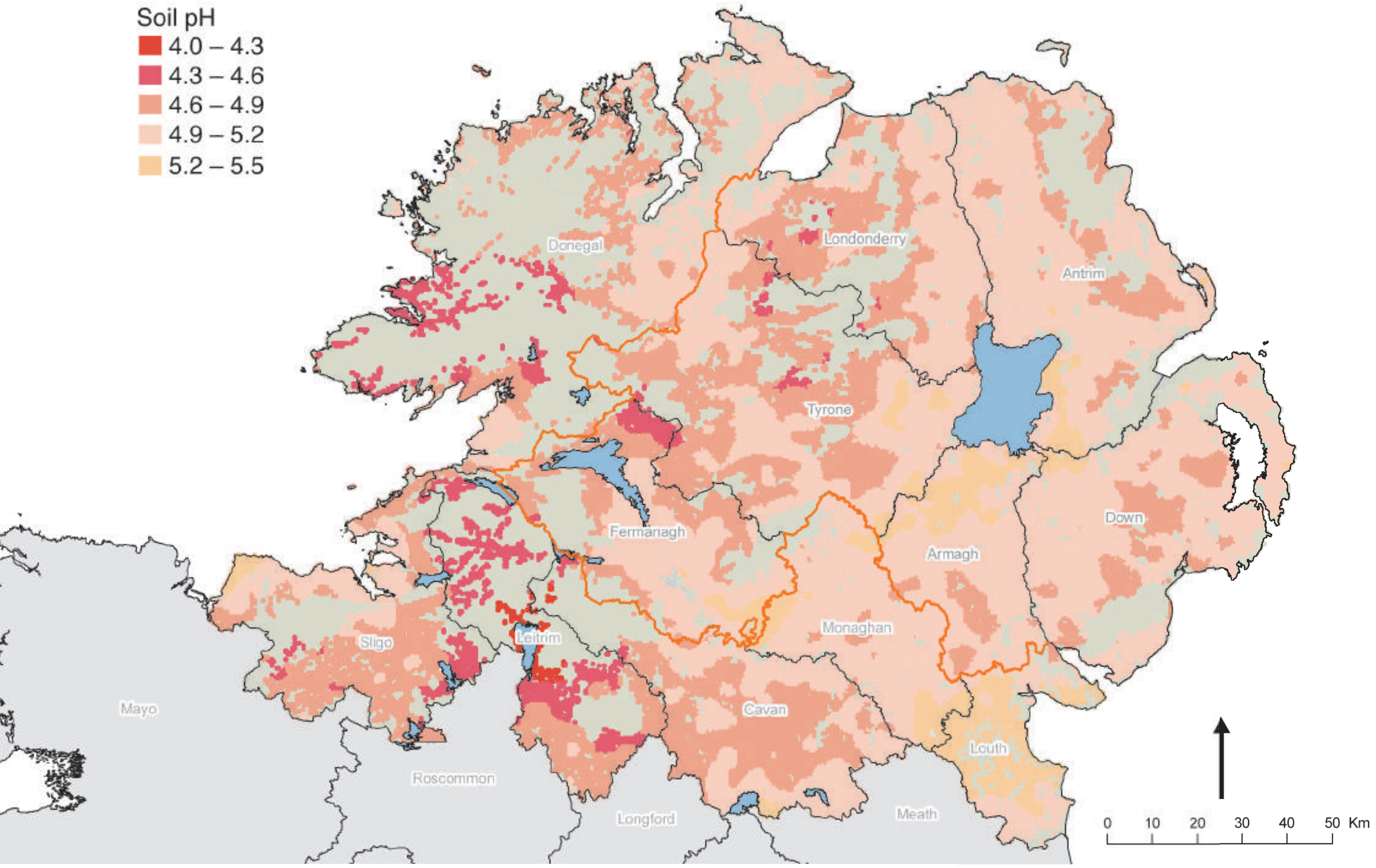


Figure 15.3. Predicted soil pH at locations under pasture. Light green indicates other land use.

the short-range variation described by the nugget variance. Short-range variations remain unknown, unless further local sampling is done, but in the geostatistical setting we can quantify their effect on our uncertainty about local soil conditions.

## Prediction

The objective of geostatistical prediction is to obtain interpolated values of a variable at unsampled locations. In geostatistics the interpolation is done by the kriging predictor which forms a linear combination of local values of a variable to obtain the prediction that is optimal in the sense that the expected squared prediction error is minimised. In this study we used the disjunctive kriging (DK) predictor. More details on this method are given by Webster and Oliver (2007). DK provides a predicted value at an unsampled location. In addition it allows one to compute the probability that the true value at that location exceeds some threshold, conditional on the observations. Thus, for example, if the predicted value of soil pH at some location is 6.0, this suggests that it is within an acceptable range for pasture (larger than the target value of 5.9). However, there is uncertainty in the prediction, because of the spatial variability of soil pH, and particularly because of the substantial short-range variation that is represented by the nugget variance. The value of DK is that one can also compute the probability that the true pH at the location of interest is less than 5.9 and remediation is required. This probability may be substantial.

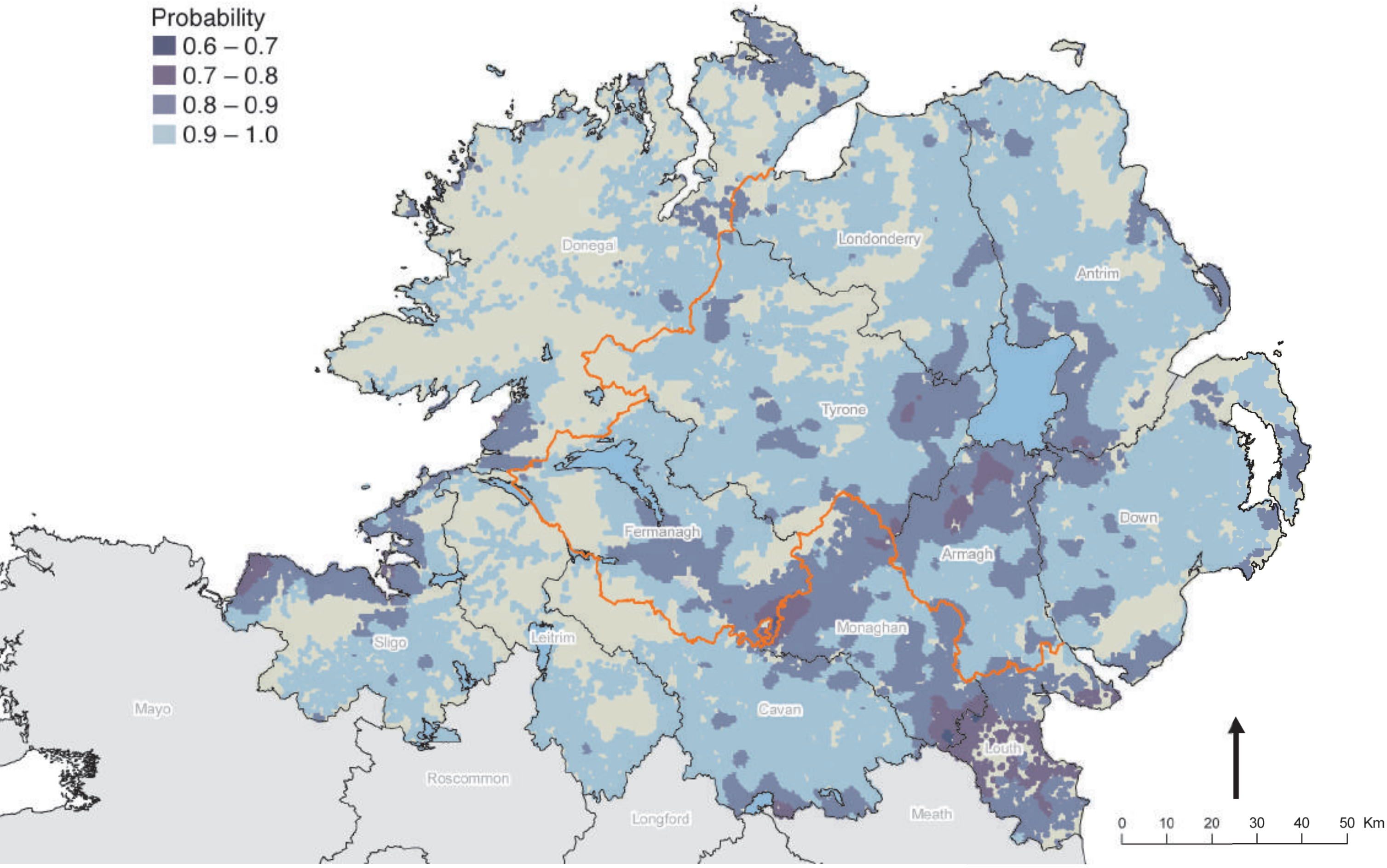


Figure 15.4. Probability that true pH is less than 5.9 in pasture soil. Liming indicated for clover-based pasture systems. Light green indicates other land use.

Figure 15.3 shows the DK predictions of soil pH across the study region at locations on a 500 m grid which are in CORINE land cover class *Pasture* (class 231) according to the CORINE data (CORINE, 2006). Non-pasture nodes of the grid are coloured green – largely areas of peat deposits, moorland, large urban areas (e.g. Belfast) or arable farming (e.g. County Louth). Soils adjacent to the extensive peat deposits in counties Sligo and Leitrim have the lowest pH values (<4.3) of the pasture soils. It is likely that these soils are also very organic-rich and have a naturally very low pH, but do not meet the criteria of 'peat' in the CORINE mapping classes. Lower pH values (<5) are also found in the uplands of the Sperrin Mountains, and County Donegal. These uplands are generally formed of rocks with limited amounts of calcium and magnesium, which restricts the capacity of the soil to buffer acidifying processes. Uplands also have the largest rainfall, which contributes to the physical and chemical erosion of pH-buffering soil minerals. In contrast, soils formed over the Antrim basalts typically have a higher pH. This is because the minerals forming the basalt contain a lot of calcium and magnesium, which increases the buffering capacity of the soils formed over them. The exception to this is over the north-east Antrim uplands, where thick peat deposits are found, giving rise to acid soils in their immediate periphery. The Carboniferous limestone rocks of the more southerly counties in this area also typically have a higher pH in soil, as the primary rock mineral is calcium carbonate. County Louth has larger pH values than much of the region, resulting in part from the

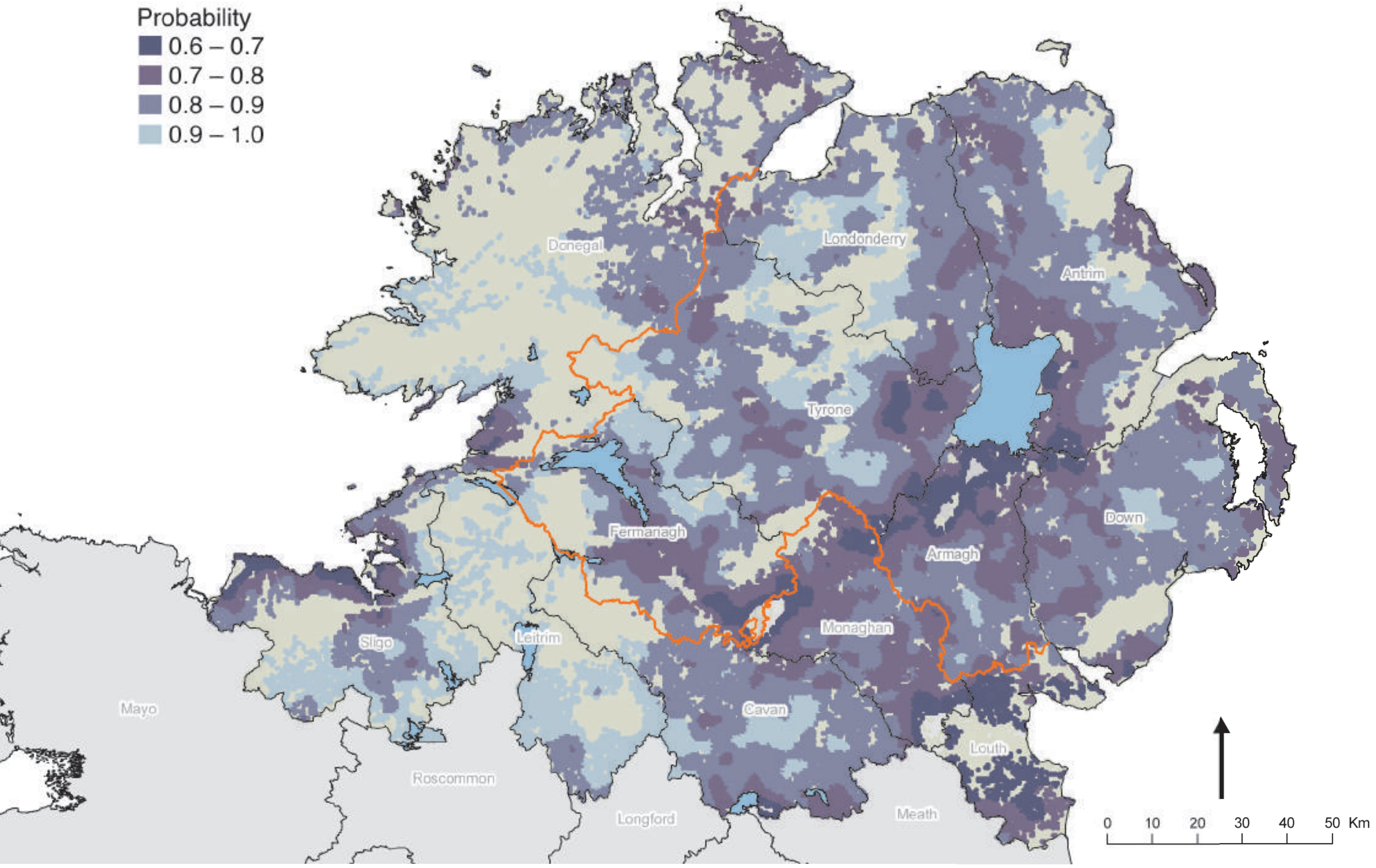


Figure 15.5. Probability that true pH is less than 5.4 in pasture soil. Liming indicated under RB209 guidelines. Light green indicates other land use.

larger calcium and magnesium concentrations in the underlying Lower Palaeozoic rocks, but also from lime inputs in this more intensively managed agricultural landscape.

Figure 15.4 shows the probability that soil pH in pasture soils falls below the 5.9 target (6.5 in water) that Coulter and Lalor (2008) advise for pasture. Note that at all locations this probability is larger than 0.5. Figure 15.5 shows the same probabilities for the 5.4 target (6.0 in water). Figure 15.6 shows the probability that soil pH in pasture soils falls below the value of 5.0 which was a minimum for various earthworm species on Park Grass.

Figure 15.7 shows probability distributions obtained by DK for soil pH at two locations. These plots show the probability that the true value at each site falls in each discrete range of values; they are not histograms. At both the predicted value is about 4.5, but at location A there is less uncertainty in the prediction; the distribution is much narrower than at B. This partly reflects the difference in sampling density between the Tellus Border (B) and Tellus surveys (A). However, even at location A the prediction distribution is 2 pH units wide. This reflects the uncertainty of any point prediction due to the substantial short-range 'nugget' variability of pH.

## Communication

Given the substantial short-range variation of soil pH, illustrated in Fig. 15.7, it is not, in general, advisable to make local decisions as to whether or not to remediate without

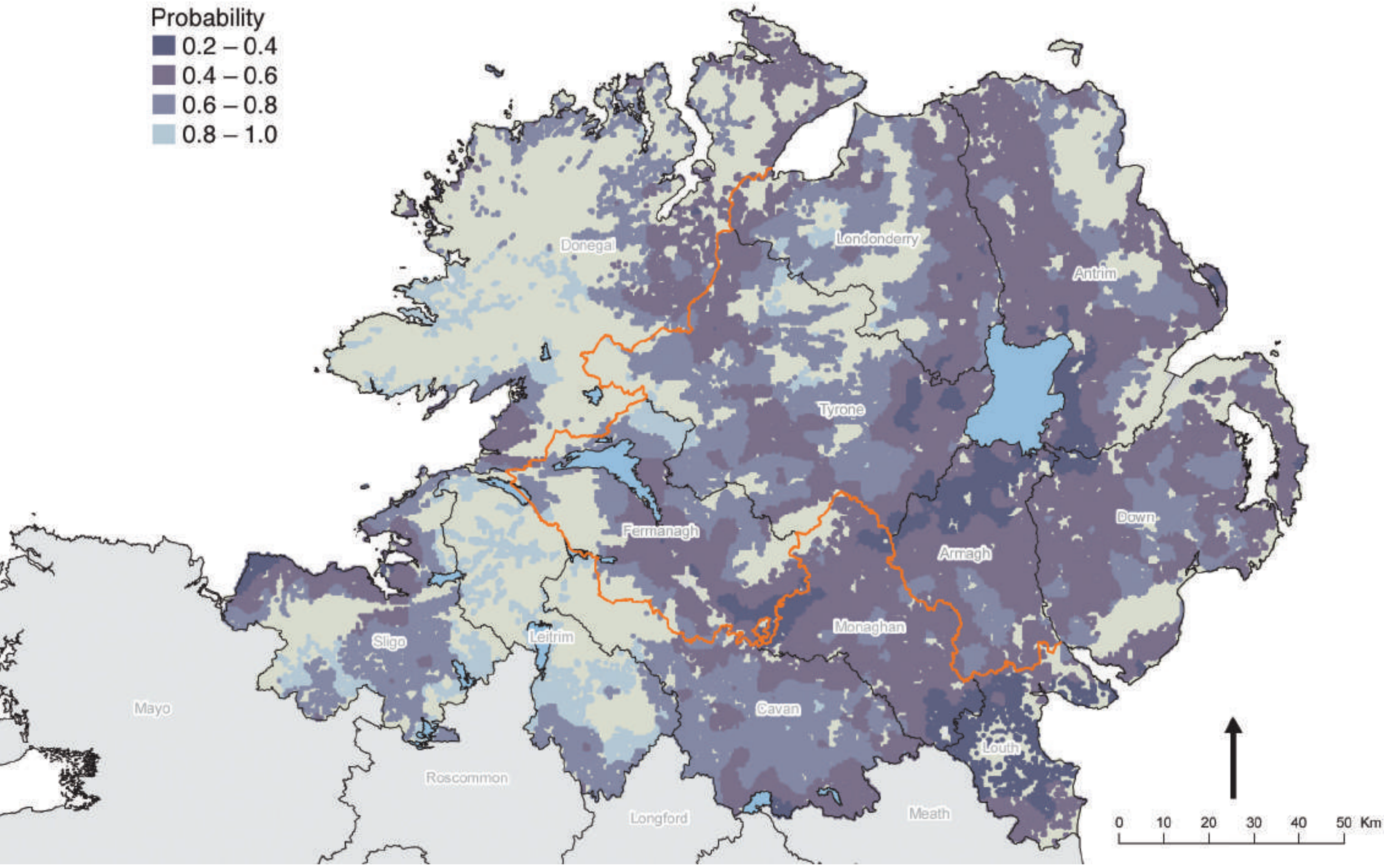


Figure 15.6. Probability that true pH is less than 5.0 in pasture soil, indicating limitations on sensitive earthworm species. Light green indicates other land use.

local sampling. However, for strategic or policy purposes it may be useful to consider the general spatial pattern of the expected pH and probability that pH is less than the target value, perhaps to form overall estimates of the limiting effect of soil on pasture productivity at regional scale, or to target extension work. Users of these data must understand the associated uncertainties. In particular, farm managers need to understand the information on the probability that their land has a pH below the target so as to make informed decisions on whether to undertake further sampling. In this way the regional data can facilitate decision making, although local sampling is also required.

The geostatistical analysis that we undertook allows the uncertainty about local pH values to be expressed in terms of probabilities, including probabilities that the local pH falls below a threshold at which an intervention is indicated. These probabilities reflect general trends in soil pH and also the uncertainty introduced by short-range spatial variability. Thus, for example, at a location where the predicted value of soil pH is above the target value, the probability that the true value is below the threshold may still be large. This will depend on the local density of sampling and the local variation. While probability maps such as Figs 15.4–15.6 are an effective means to represent the uncertainty in geostatistical predictions, they are not necessarily effective for communication to non-specialists (Spiegelhalter *et al.*, 2011). For this reason we have used 'calibrated phrases' to communicate the uncertainty that the probabilities represent. Specifically we use the

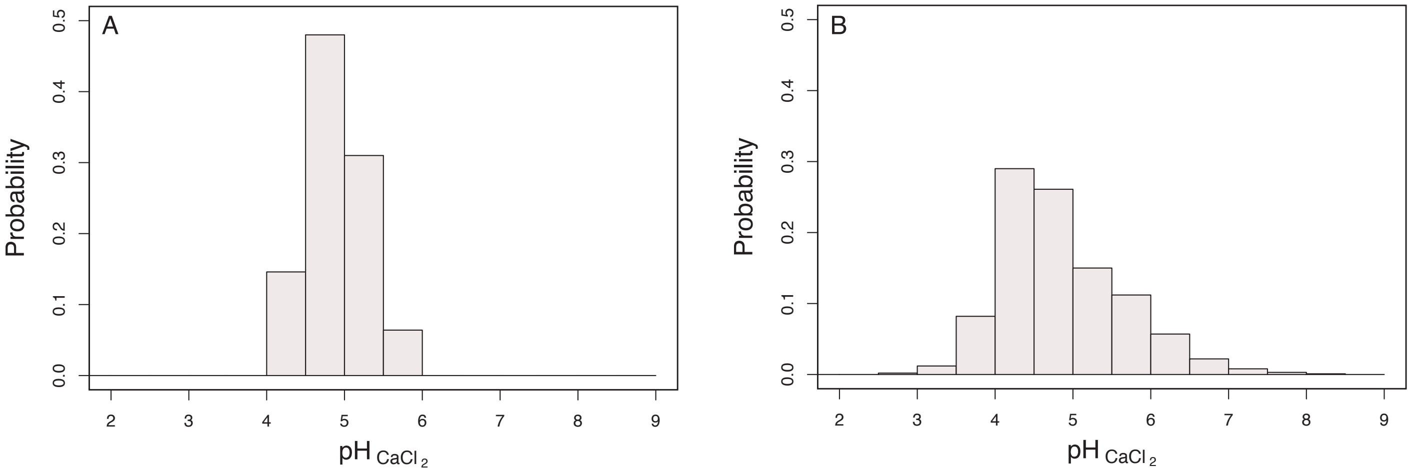


Figure 15.7. Probability distributions for pH at two locations, A and B. The expected values at the two locations are very similar (about 4.7).

scale that the Intergovernmental Panel on Climate Change (IPCC) stipulates for use in scientific reports aimed at a general audience (Mastrandrea *et al.*, 2010). If some outcome has probability $P$o and $P$o ≥ 0.66 then it is described as 'Likely' on the IPCC scale. This is intensified to 'Very likely' if $P$o ≥ 0.9 and to 'Virtually certain' if $P$o ≥ 0.99. The outcome is described as being 'About as likely as not' if 0.33 ≤ $P$o < 0.66. If $P$o < 0.33 then the outcome is described as 'Unlikely', intensified to 'Very unlikely' if $P$o < 0.1 and to 'Exceptionally unlikely' if $P$o < 0.01.

In a previous paper (Lark *et al.*, 2014a) we used the IPCC scale to convey uncertainty about geochemical information. We took account of some recent research on the efficacy of the scale to modify how we presented it, in particular including some numerical information along with the verbal phrases. Figures 15.8 and 15.9 use these principles to convey the probability that soil pH indicates, respectively, that liming is required on clover-based pasture systems and that soil pH is a limitation on sensitive earthworm species.

## Conclusions

The most immediate practical conclusion from this study is that most pasture soils across the north of Ireland appear to be in need of liming. In terms of the verbal scale it is *likely* that liming is required at all pasture sites across the region, and this can be intensified to *very likely* across 64% of the study region (Teagasc-recommended threshold for clover-based pasture systems) and *virtually certain* in some places, particularly in the west (constituting 5% of the study region). On this basis farmers should be advised to test their soil pH and to seek advice on lime requirement. This is particularly urgent in areas where the pH is *likely* to be limiting on activity of certain earthworms (23% of the study region), given their important role as 'ecological engineers'.

Soil pH is more subject to temporal (decadal) change at broad spatial scales than most geochemical variables (e.g. Kirk *et al.*, 2010) due to land use change, management and

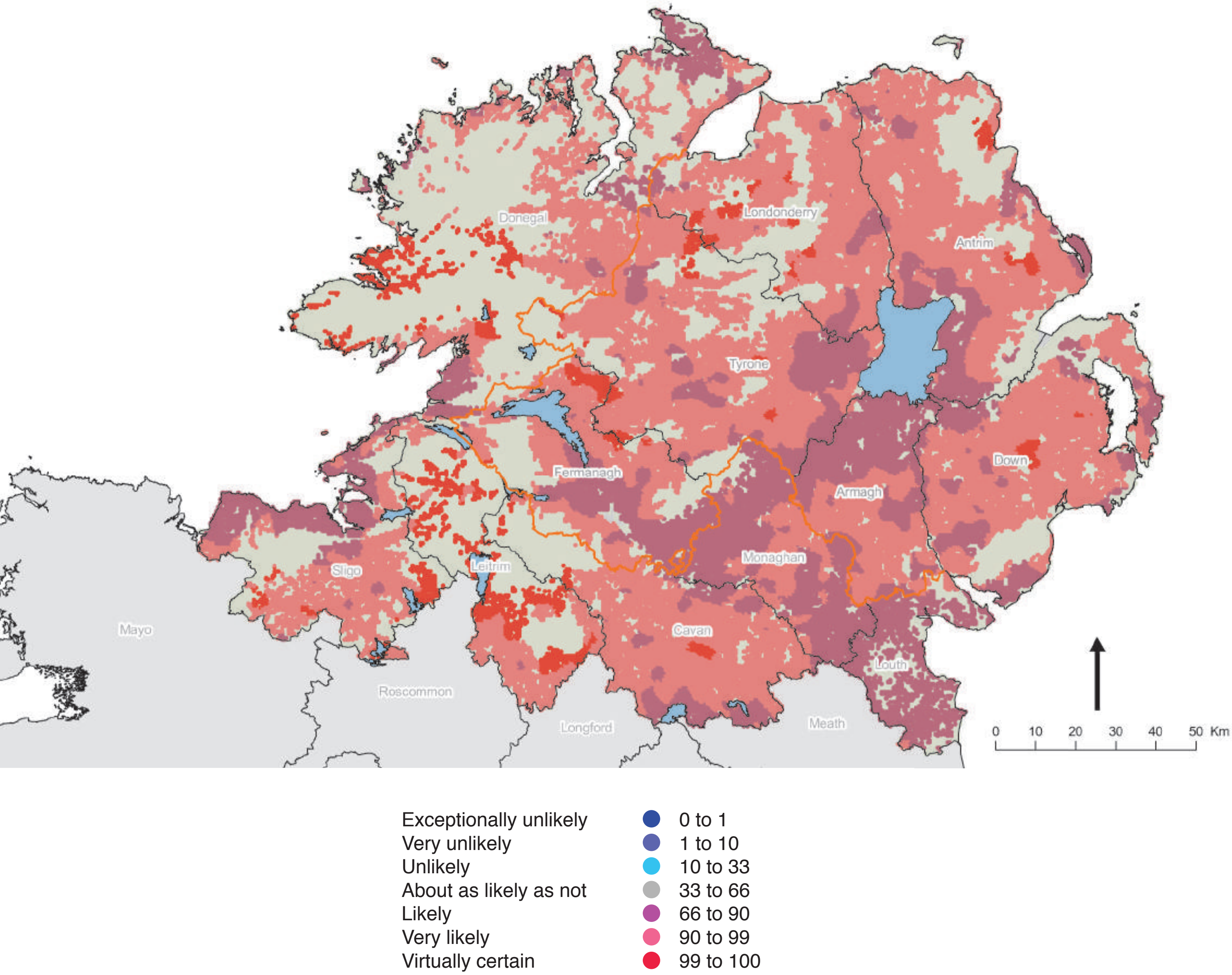


Figure 15.8. Probability that liming is indicated for clover-based pasture systems, communicated using the IPCC verbal scale. Light green indicates other land use.

changes in acid inputs, both anthropogenic and natural. For this reason it is necessary to monitor change in soil pH to detect emerging problems and ensure that advice is based on current information. Our results show that soil pH exhibits substantial short-range variation. The design of a robust sampling scheme requires further investigation of this short-range variation to ensure that monitoring is sensitive and fit for purpose (e.g. Lark *et al.*, 2014b).

This study exemplifies some general lessons about the use of regional geochemical surveys as a basis for advice to farmers. First, it is clear that substantial local variability can contribute to uncertainty about local predictions. Appropriate statistical treatment and communication can ensure that the results are not misleading, but there is also scope for further work on how, for example, the regional survey might be used to indicate to producers the potential value of additional soil information, and guidance on appropriate

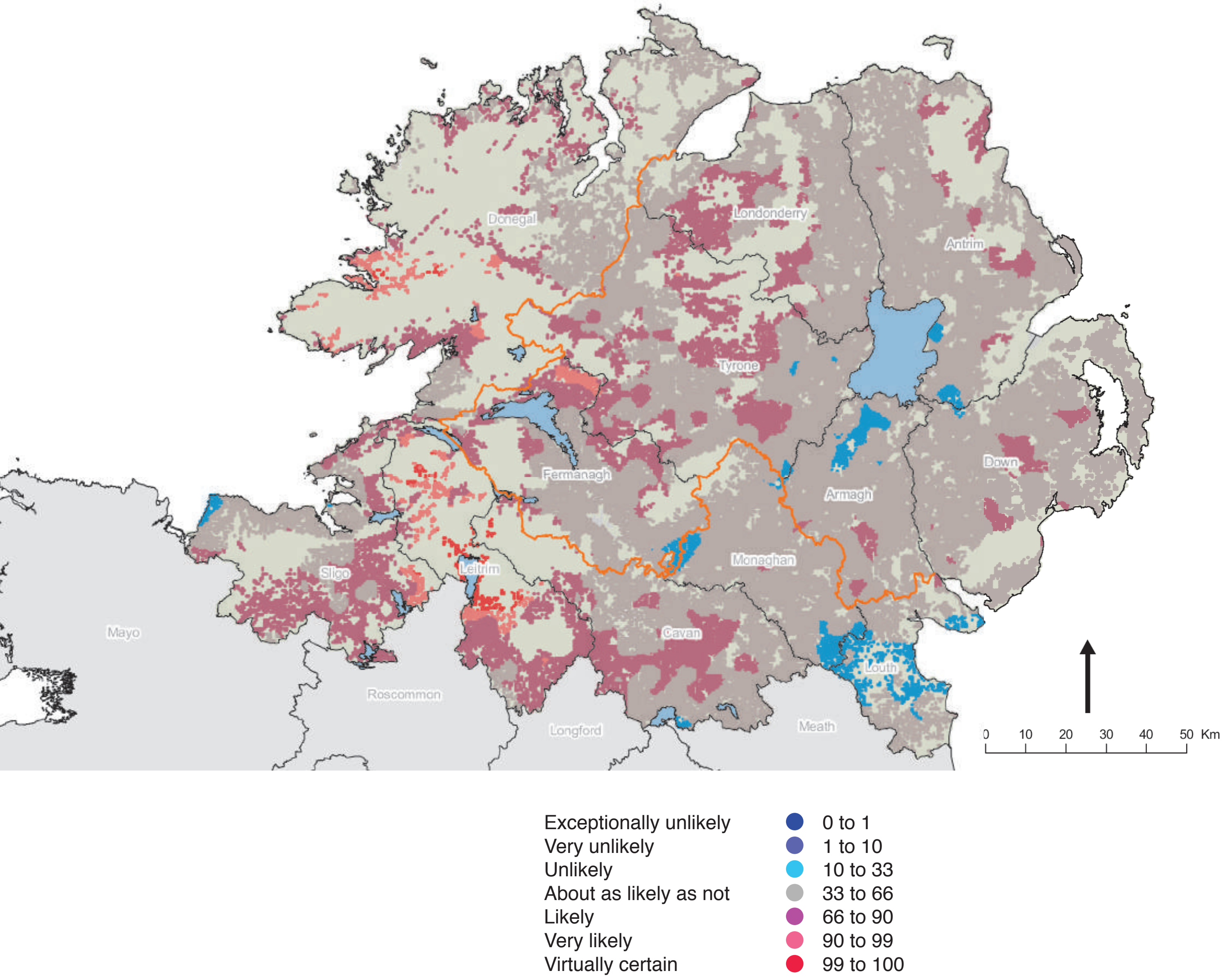


Figure 15.9. Probability that soil is too acid for sensitive earthworms, communicated using the IPCC verbal scale. Light green indicates other land use.

sampling to collect it. Second, the study illustrated the fact that the data in a geochemical survey are not necessarily directly appropriate for agricultural use. Here we had to convert pH values measured in $CaCl_2$ to expected values in water, because this is the variable on which advice is based. Similarly the total concentrations of elements in geochemical surveys are not, in general, comparable to the 'available' concentrations on which agronomic advice is based. Available nutrients (such as nitrogen, phosphorus, potassium, magnesium and sulphur) could be added to the suite of analyses in further geochemical surveys. Further work on the potential value of standard geochemical variables as predictors of agronomically useful properties such as soil pH buffering capacity or exchange isotherms for key nutrients would also be useful.

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