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Degradation rate of soil function varies with trajectory of agricultural intensification

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ABSTRACT

Efforts to maintain or increase food production in developed agriculture would be compromised if current high-intensity production was degrading supporting ecosystem services, such as the ability of soil to function. The link between cropping intensity, defined by pesticide and fertiliser applications, and soil biophysical status was examined at 70 sites in a high-yielding region of the UK, in which cropping sequences covering a wide range of intensity had diverged from a common low-intensity origin in the 1970s. Two sequences of still low or moderate intensity based on spring cereals or a low frequency of winter cereals formed comparators for three high intensity sequences based on winter wheat and potato which together were associated with adverse effects of −30% on soil carbon content in the upper soil layer ($P < 0.001$), −11% on soil water holding capacity ($P < 0.01$) and +15% on soil bulk density ($P < 0.001$). Negative effects were also found in some high intensity sequences on soil macroporosity and penetrometer resistance. Even in this high-yielding region, therefore, current forms of intensification are associated with adverse trends in soil condition that may be detrimental to future production. The effects of these trends in soil condition on agricultural output now need to be quantified, and the economic burden accounted for, if fields reduce their capacity to yield or need reparation to keep them productive.

1. Introduction

The aim to increase food production has to contend with current limitations in the genetic potential of crops, in their associated agronomic inputs and in the capacity of fields to support continuous, high levels of plant growth and yield (Evans, 1993). The third of these, dependant on the functioning of fields, is perhaps the least understood limitation in developed agriculture. Yet if new varieties were to be produced with superior physiological traits, their potential would not be realised if the supporting functions of the fields were themselves deteriorating.

The widespread negative effects of agricultural intensification on the ecology of farmland (Royal Society, 2009) have been well documented, but mainly for plants, insects and birds (Donald et al., 2001; Marshall et al., 2003; Firbank et al., 2013; Stoate et al., 2001). Comparable knowledge for the essential functions provided by soil is less convincing, partly because the degradation of soil functioning tends to be reported and tabulated only in very general terms in relation to large-scale agricultural change (Smith et al., 2013; Firbank et al., 2013; Powlson et al., 2011). Moreover, the impacts of modern agriculture on soil properties may not be generic among different forms of cropping practice; rather, they may differ according to crops, operations, cropping sequences and type of soil. There has, however, been little tracking of change in the biophysical attributes of soil in commercial agricultural fields in relation to any recent transitions to higher intensity. For example, surveys in the UK showed a general decline in soil organic carbon under arable and horticultural production by about one third between 1978 and 2007 (Emmett et al., 2010), but were not designed to examine whether the decline was caused by, or differed in relation to, the type and intensity of field management.

It has also been difficult to establish where a decline in soil function has led to a specific reduction in productivity by crops. Admittedly, if the range of soil condition being considered is very wide, then limitations to yield have been assigned variously to shallow depth, low carbon content and water-holding capacity, low pH or salinity (Lal, 1997). However, in a region of developed agriculture such as north-west Europe, inputs of fertiliser and pesticide can be manipulated to overcome small limitations due to soil condition, such that a slow degradation in supporting function may not be noticed. The associations between a particular trajectory of intensification, the resulting condition of soil as a medium for crops and the effect on yield and other outputs therefore still needs to be determined.

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The challenge in quantifying effects of past intensification on soil functioning is in finding suitable comparators, since pre-intensification fields have mostly disappeared in developed commercial agriculture. A realistic alternative comparison would be between fields that have followed divergent trajectories of greater or lesser intensification over recent decades. A potential comparison of this type exists in an area of productive maritime agriculture, whose cereal yields rank highly within Europe, implying the crops are subject to few overriding physical and climatic limitations compared to those in many other regions. The latest phase of intensification began in the 1970s with an increase of inputs to all crops and an increase in area sown with high-intensity crop sequences (Economic Report on Scottish Agriculture, 2013, and previous reports). Crucially, the most intense forms of production have not been uniformly adopted, such that high intensity and low intensity sequences are still grown commercially in the same landscape. The aim of this study is to define the trajectories of intensification that have occurred over the previous 40 years, to quantify their end points, in terms of the present range and type of intensity, and to test the null hypothesis that differences in intensification have no effect on the biophysical status of soil. The implications for feedback between intensification, high yield and supporting ecosystem services are considered.

2. Methods

2.1. Sites and crops

To facilitate a network of field sites for long term scientific study, farmers had nominated fields that had been managed according to a range of principles and purposes. The aim of this specific study was to compare effects resulting from intensity of inputs (more or less fertiliser and pesticide) rather than different kinds of practices and inputs (e.g. stock raising compared to crop production based on inorganic fertiliser). The commercial, arable standard for the maritime agricultural region of the east of Scotland is a cereal-based sequence of crops given inorganic fertiliser and chemical pesticide, and therefore this type of agriculture was chosen for the study.

Since the relations between cropping history, management intensity and soil condition were unknown before the analysis presented later in this paper, fields could not be selected in advance to test specific hypotheses. Therefore, to account for potential effects of variation in soil, climate and management intensity, fields of broadly different putative management (e.g. mostly winter crops or mostly spring crops) were sampled throughout the area of 'prime arable land' in the East of Scotland (see map in Hawes et al., 2010). In total, 71 fields conformed to these requirements. The sites were distributed over a latitudinal range of 231 km, centred around latitude 56°N and within 35 km inland from the coast.

From south to north, daylength and solar altitude differ by only 3% and incoming solar radiation in summer by less than 10%. Other climatic factors, such as temperature, are less dependent on latitude and more on distance from the sea: a slight fall in temperature and rise in wetness (fall in droughtiness) occur with distance inland, subject to variation due to local topography and proximity to major estuaries. These climatic gradients are relatively small compared to those over the UK or north-west Europe as a whole. (Further information is given in Supplementary material A.) The region consistently produces the highest average cereal yields in the UK due to long cool summers that draw out phasic development of the crops and thereby ensure high interception of the incoming solar radiation. The main categories of management intensity (found through the analysis later in this paper) were distributed throughout the latitudinal range, as described in Supplementary material A.

Previous management was not consistently or reliably recorded in all fields, so an assessment of nominal intensity was made from attributes of the crops grown in the five years before sampling, a period in which most crops typical of a sequence would be grown at least once (see Section 2.2 for method). These previous crops were condensed into thirty categories, each termed a 'crop type', defined by species and by season of sowing. As a percentage of sites in which they were grown at least once, and the percentage of site-years occupied, the most common crop types were spring barley (70.8% of sites, 28.3% of site-years), winter wheat (67.7%, 23.7%), winter oilseed rape (43.1%, 10.5%), winter barley (32.3%, 9.8%), set aside (12.3%, 2.8%) and ware potato (24.6%, 4.8%). Others, such as spring bean, spring wheat, winter and spring oat, legumes, leaf brassicas, 'root' brassicas, set aside, fallow and grass, were each found in only a few site-years. Potato and brassica vegetables was sometimes grown in different years in a field, giving the additional category 'potato and vegetables'. In total, cereals occupied 68.3% of all site-years and at least one cereal was grown at each site within the 5 year period. Only spring barley and winter wheat were grown frequently enough to assess the effect of the number of crops of a given type (0–3) in the five year sequence.

2.2. Nominal intensity of management

Government census data for Scotland were used to define the trajectories of intensification in arable cropping since the 1960s and to derive indicative measures of intensity over the previous five years for each field in the study. To obtain the trajectories of intensification for the main crops, data were collated by year for area sown and yield of spring barley (SB) and winter wheat (WW) from the Economic Report on Scottish Agriculture (2013) and previous reports back to the 1960s. The only consistent, available indicators of intensity were applications of pesticide and fertiliser. Use of pesticide was obtained from surveys that began in 1974, occurred sporadically up to the 1990s and then every two years subsequently (Struthers, 2007), and earlier reports in this series. For each type of crop, the area treated with 'formulations' (the latter defined as the active ingredient or mixture of active ingredients in a product) was accumulated for each product – molluscicide, insecticide, fungicide, herbicide (seed treatments excluded) – and then divided by the area on which the crop was grown to give a 'pesticide area index' (PAI), which is indicative of the number of pesticide applications that a crop-type received. Formal surveys of fertiliser use began in 1942 in England and Wales but not until 1983 in Scotland (Fertiliser Practice, 2013; Church and Lewis, 1977) before which values were adjusted from those in England and Wales. Values of nitrogen, phosphate and potash used were those designated in the census as 'average field rate' for the region 'Scotland'.

Nominal estimates of intensity for each field in the study were obtained from the census data for fertiliser and pesticide for the actual crop-types grown in each field in the five years before sampling (2003–2007) and averaged over the period. Since phosphate and potash were highly correlated, an overall relative indicator for each field was calculated by averaging values of nitrogen, phosphate and pesticide for each field as a fraction of the respective mean. The methodology for estimated intensity in this way, together with worked examples from the whole range of intensity, is given in Supplementary material B.

Estimates of yield were provided by farmers for around half the fields, but were unverified by additional measurements. Reliable inputs of fertiliser and pesticide were provided for the sample year for many of the fields (Hawes et al., 2010) and were generally close to the national average from the census. For example, the mean