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Quantifying the spatial variability of soil physical and chemical properties in relation to mitigation of diffuse water pollution

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ABSTRACT

Understanding spatial variability of soil properties in response to land-use impacts is essential for evaluating the effectiveness of measures taken to address diffuse water pollution from agriculture. However, despite the growing emphasis on integrated catchment-scale implementation of land-use mitigation measures, the baseline landscape-scale evaluation of the spatial variability of key soil nutrients remains scarce. This study employs a high resolution geostatistical approach to characterise the spatial variability of parameters, including soil bulk density (BD), total soil carbon (TC), nitrogen (TN), phosphorus (TP), inorganic phosphorus (IP), organic phosphorus (OP), stable nitrogen isotope ratio ($\delta^{15}N$), C:N ratio, carbon storage and nitrogen storage in two study catchments with contrasting land uses (agricultural and semi-natural) that are subject to targeted management interventions to reduce flood risk and improve water quality. We found a stronger degree of spatial dependence of all soil properties in the agricultural than the semi-natural catchment, except for bulk density and $\delta^{15}N$. Furthermore, bulk density, TP, IP, OP, C:N ratio, $\delta^{15}N$ and carbon storage showed a longer range or spatial autocorrelation in the agricultural catchment. The central tendency (median and mean) of all soil properties was also significantly different between the two catchments, with the exception of IP and $\delta^{15}N$. The spatial correlations between the soil properties pointed to the mechanisms that were responsible for the observed differences, whilst the krigged surfaces of soil variables identified most likely critical source areas for targeted land management interventions to improve water quality. Arable and intensive grasslands were identified as 'high-impact' land uses, associated with negative alteration of soil properties and increased diffuse water pollution, whilst moorland was a 'low impact' land use associated with improved water quality. A comparison with the national soil survey dataset shows that whilst it can be relied upon for the broad characterisation of carbon and TP stocks in the two study catchments, it underestimates the spatial variability of key soil properties in certain soil types and land uses. As the restoration of soil spatial heterogeneity may take several decades, a high resolution geostatistical approach should be included in the future design of catchment-scale monitoring schemes to inform catchment management strategies and elucidate the time frame over which landscape scale improvements in soil properties and corresponding ecosystem services can be achieved.

1. Introduction

Characterising the spatial variability of soil properties is essential for the understanding of the effects of land management on soil function and associated ecosystem services, including those involving water quality, carbon (C) sequestration and biodiversity (Cambardella et al., 1994; Dixon et al., 2010; Ettema and Wardle, 2002; Goovaerts, 1998; Stutter et al., 2009). This understanding of the heterogeneity of the soil resource is necessary for an effective design of experimental sampling (Oliver and Webster, 1991) and optimal evaluation of the effectiveness of diffuse pollution mitigation measures to protect receiving surface waters (Peukert et al., 2012; Rivero et al., 2007). However, still too few studies describe spatial variability of multiple soil properties and their inter-relationships at a landscape scale (Bruland et al., 2006; Liu et al., 2010; Paz-Gonzalez et al., 2000; Rivero et al., 2007; Stutter et al., 2009), despite the growing need to assess the effectiveness of soil management measures designed to mitigate diffuse water pollution from agriculture at the catchment scale. Herein, it is argued that understanding the variability of soil properties at a landscape scale will inform the prioritisation of areas for restoration and management (Bruland et al., 2006) and therefore as such is a useful tool to aid soil use and management decision-making process.

Abbreviations: C, carbon; N, nitrogen; P, phosphorus; TC, total soil carbon; TN, total soil nitrogen; C:N, carbon to nitrogen ratio; $\delta^{15}N$, stable nitrogen isotope ratio; TP, total soil phosphorus; IP, soil inorganic phosphorus; OP, soil organic phosphorus.

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As soil is a continuum, its spatial properties have to be auto-correlated at a certain scale (Oliver and Webster, 1991) and hence any quantitative analysis of soil properties has to take into account the spatial coordinates of the observations (Goovaerts, 1998). Geostatistics allows for the quantification of the degree of spatial auto-correlation between environmental properties and subsequent use for prediction of values at unmeasured locations (Oliver and Webster, 1991; Webster and Oliver, 2001), enabling the quantification of the scales of spatial variability (Stutter et al., 2009) and facilitating a better understanding of the mechanisms and processes that control spatial patterns (Goovaerts, 1998).

Nutrient content, distribution and supply have a profound influence on the functioning of ecosystems (Fraterrigo et al., 2005). The role of increased phosphorus (P) and nitrogen (N) loading in causing eutrophication of freshwaters is widely accepted (Pierzynski et al., 2000; Wang et al., 2009), whilst alterations to the terrestrial–aquatic linkages in dissolved organic carbon (DOC) dynamics are likely to have multiple effects due to its wide-ranging role in the functioning of aquatic ecosystems (Stanley et al., 2012). Intensive land use has been proven to have long-term effects on soil properties, including bulk density (Fraterrigo et al., 2005) and soil organic matter (Bradford et al., 2008). Tillage and addition of inorganic P and N fertilisers accelerate the decomposition of organic matter (Bradford et al., 2008; Brady and Weil, 1999; Zhang et al., 2012), resulting in the alteration of soil physical, chemical and biological properties (Brady and Weil, 1999; Senbayram et al., 2008). However, land management has also subtle long-term effects on the spatial heterogeneity of soil resources which may not be apparent when the averaged values are compared between sites and soil types (Fraterrigo et al., 2005). Whilst agricultural land use has been shown to reduce the spatial variability of soil properties through cultivation, fertiliser application and grazing (Gilliam and Dick, 2010; Li et al., 2010; Paz-Gonzalez et al., 2000), the natural variations in the spatial distribution of physical and chemical soil properties in temperate upland moorland soils are less understood (Stutter et al., 2009). Further research is therefore urgently needed to quantify alterations in soil spatial variability resulting from changes in land use (Li et al., 2010) in order to aid accurate estimation of nutrient budgets and cycling rates (Fraterrigo et al., 2005; Stutter et al., 2009) and identify possible terrestrial sources of pollution to aquatic ecosystems.

With these research needs in mind, this study takes a high resolution catchment-scale geostatistical approach to characterising the baseline spatial distribution of the key macronutrients; C, N and P to identify possible sources of nutrient pollution and support evaluation of diffuse water pollution mitigation schemes. Specifically, this research focuses on two neighbouring catchments, one upland the other lowland, with contrasting land uses that are subject to targeted land management interventions in order to alleviate flood risk and reduce diffuse water pollution. The upland catchment is dominated by semi-natural moorland and woodland habitats, whilst the lowland catchment has more intensive agricultural management. We hypothesised that the spatial variability and the central tendencies (median and mean) of soil properties in the two study catchments with contrasting land uses will differ and that only the data provided by a high resolution geostatistical approach will be able to provide a sound baseline for current and future monitoring of the effects of land-use (and management) changes on soil nutrient concentrations and stocks.

Specifically, we therefore aim to:

1. characterise and compare the catchment-scale spatial variability and central tendencies of various soil properties, including bulk density, total C (TC), total N (TN), total P (TP) and the stable N isotope ratio ($\delta^{15}N$) between two contrasting study catchments;
2. elucidate possible mechanisms controlling the observed spatial variation;
3. provide a baseline dataset for monitoring the effectiveness of land management interventions to mitigate diffuse water pollution from agriculture at a catchment scale in the medium term;
4. compare the characterisation of spatial variability and nutrient stocks (C and P) obtained in this study using the detailed geostatistical approach with their respective mean soil values recorded in national datasets.

2. Methods

2.1. Study site

The two study catchments, Aller and Horner Water, are located in south-west England on the north-east edge of Exmoor National Park (51°11′52 N 3°34′41 W) (Fig. 1). The Aller catchment covers 17.6 km^2 with an altitude range of 4–425 m above sea level whilst the Horner Water catchment covers 22.0 km^2 with an altitude range of 20–516 m above sea level. The 30-year average annual rainfall for the period 1961–1990 for Horner Water catchment is 1489 mm and for the Aller it is 1056 mm (Spackman, 1993), due to the predominantly upland nature of the former, and lowland nature of the latter catchment. The average annual temperature for the two catchments is 11–12 °C (Met Office, 2011).

The soils within the two catchments are predominantly loamy brown earths and podzols. In addition, clayey calcareous and argillic pelosols are present in the lowest lying areas of the Aller catchment, whilst peaty-topped loamy stagnopodzols and stagnohumic gley soils are found on the highest ground of Horner Water catchment (Soil Survey of England and Wales, 1983).

Land use in the Aller catchment is dominated by livestock rearing, primarily sheep, with a smaller number of cattle and ponies. The upper tributaries originate from unimproved heathland and permanent semi-improved grassland. Further downstream most of the grasslands are improved, with the exception of the steepest sloping ground at the catchment edge. Livestock are fed on home-grown hay or silage from short-rotation leys, on roots and imported concentrates. Arable land is rotated between short-term grass leys, winter wheat/spring barley, roots and peas, with maize grown at the eastern end of the catchment. Soil fertility is maintained through applications of solid farm-yard manure and inorganic NPK fertilisers, which are typically applied in the spring before the start of the growing season. In the Horner Water catchment, semi-natural vegetation, including oak woodland and upland heathland, predominates and agricultural land use is mostly extensive livestock grazing, with very limited arable farming occurring on the flat plateaux in the west of the catchment.

2.2. Field sampling and laboratory analysis

2.2.1. Soil sampling

A combined strategy of stratified spatially distributed soil sampling was applied to allow for the requirements of both classical statistics, and geostatistics. The soils described are the lead series of the soil associations found in the two catchments according to the National Soil Map (Soil Survey of England and Wales, 1983); specifically for this study they have been grouped into three broad texture categories of clay, loam and peat (having a peaty topsoil), as characterised in this dataset (Findlay et al., 1984) (Table 1). Four land-use categories were also defined: arable and grass ley, permanent grassland, moorland and woodland, based on land-use data from UK conservation agencies and field survey. Twelve random sampling points, with a minimum distance of 50 m between individual samples, were identified for each soil type and land-use combination in both catchments, using an ArcGIS 9.3.1. sub-routine for random point generation (ESRI, Redlands, CA, USA). Overall, a total of 205 soil samples were collected in July and September 2010 in the Aller and Horner Water catchments, giving an overall sampling density of 5.18 samples km^2. Sampling density in the Aller