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Indicators and trade-offs of ecosystem services in agricultural soils along a landscape heterogeneity gradient

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ABSTRACT

Soil functions can be classified as supporting (nutrient cycling) and provisioning (crop production) ecosystem services (ES). These services consist of multiple and dynamic functions and are typically assessed using indicators, e.g. microbial biomass as an indicator of supporting services. Agricultural intensification negatively affects indicators of soil functions and is therefore considered to deplete soil ES. It has been suggested that incorporating leys into crop rotations can enhance soil ES. We examined this by comparing indicators of supporting soil services – organic carbon, nitrogen, water holding capacity and available phosphorous (carbon storage and nutrient retention); net nitrogen mineralisation rate and microbial biomass (nutrient cycling and retention) – in barley fields, leys and permanent pastures along a landscape heterogeneity gradient (100, 500 and 1000 m radii). In addition, barley yields (provisioning service) were analysed against these indicators to identify trade-offs among soil services. Levels of most indicators did not differ between barley and ley fields and were consistently lower than in permanent pastures. Leys supported greater microbial biomass than barley fields. Landscape heterogeneity had no effect on the indicators or microbial community composition. However, landscape heterogeneity correlated negatively with yield and soil pH, suggesting that soils in heterogeneous landscapes are less fertile and therefore have lower yields. No trade-offs were found between increasing barley yield and the soil indicators. The results suggest that soil ES are determined at the field level, with little influence from the surrounding landscape, and that greater crop yields do not necessarily come at the expense of supporting soil services.

1. Introduction

Many soil functions are vital to humanity and can be classified as ecosystem services. These include nutrient cycling (a supporting service) and food production (a provisioning service) (Millenium Ecosystem Assessment, 2005; Power, 2010). Research has shown that by driving losses of soil organic carbon (SOC) and reducing microbial biomass and nutrient cycling (Birkhofer et al., 2008; Mäder et al., 2002), agricultural intensification depletes supporting soil ecosystem services. For example, intensive conventional agriculture is typified by annual crop rotations supported by annual ploughing. This leads to the breakdown of soil aggregates, stimulating organic matter mineralisation and SOC loss (Mazzoncini et al., 2011). The depletion of supporting services may undermine the ability of soils to supply provisioning services. It is therefore important to understand the relationships between agricultural practices and the delivery of soil ecosystem services.

Quantifying ecosystem services can be difficult, as most supporting services include multiple functions and their turnover rates of soil nutrients, while most measurements typically look at existing nutrient stocks. As such, certain functions and properties that are more readily measurable, and that have strong linkages to the services in question, can be used as indicators of ecosystem services (Dale and Polasky, 2007). For instance, SOC, the main component of soil organic matter, is the primary resource of the soil microbial community (Bardgett, 2005). Organic matter is degraded and decomposed by soil microorganisms; a process that releases nutrients (e.g. nitrate and phosphate) for plant uptake. Liberated nutrients are also incorporated into microbial biomass, which reduces the loss of nutrients from the system (Brussaard et al., 1997; Zhang et al., 2007). In light of this, soil microbial biomass is an important indicator of nutrient cycling, nutrient retention and soil fertility, all of which have consequences for crop production. Furthermore, the enhancement of microbial biomass requires the

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maintenance of high levels of SOC (Power, 2010), which is itself important for carbon storage and nutrient retention. Consequently, SOC, total nitrogen (TN), available phosphorous (P) and microbial biomass can be used as indicators of supporting soil ecosystem services (Bockstaller et al., 1997; Williams and Hedlund, 2013).

Breaking annual crop rotations by incorporating a perennial crop, such as a 2–5 year ley (grassland for hay production), is considered an effective means of reducing agricultural intensity and increasing SOC and TN (Robson et al., 2002). This is because the soil is not cultivated for the duration of the ley, despite the above-ground material being harvested annually. The absence of disturbance allows a build-up of organic matter through root production and carbon allocation to the soil organism community, thereby increasing quantities of SOC and TN (Christensen et al., 2009). Leys also act as a winter cover crop and can thereby reduce organic matter mineralisation and nutrient leaching, both of which can deplete SOC and TN (Kuo et al., 1997). It has been estimated that crop rotations incorporating 50% ley will store a net average of 0.8 t SOC ha^{-1} yr^{-1} (Sleutel et al., 2007). However, the use of leys or winter cover crops has not been consistently shown to increase SOC or TN relative to that of annually cropped cereal fields (Bending et al., 2004; Mendes et al., 1999).

Ley periods can also affect soil microbial communities. The short-term absence of soil disturbance has been found to increase fungal biomass (van der Wal et al., 2006), which is associated with increased soil nutrient retention (de Vries and Bardgett, 2012). The presence of a winter cover crop has been found to increase soil microbial biomass and microbial activity relative to fallow fields (Mendes et al., 1999). Ley periods are also thought to enhance the abundance of arbuscular mycorrhizal fungi (AMF), and thereby enhance soil ecosystem services through increased plant nutrient uptake and reduced soil erosion (Gianinazzi et al., 2010). The use of leys may therefore help to 'recharge' the soil microbial community and thus improve soil fertility for the subsequent crop. However, as with soil properties, differences in microbial biomass and activity between leys and cereal fields have not been consistently demonstrated (Bending et al., 2004; Jangid et al., 2008). Assumptions that the incorporation of leys within crop rotations can enhance supporting soil ecosystem services are therefore worthy of further investigation.

The landscape surrounding a focal farm field can have important effects on ecosystem services within that field. However, the study of landscape effects on agricultural biodiversity and ecosystem services has overwhelmingly focussed on above-ground processes (Blitzer et al., 2012; Tscharntke et al., 2005), with soil organisms and services largely overlooked. This may be because soil organisms are relatively immobile (Bardgett, 2005), and may thus not be expected to respond to landscape factors. However, a recent study comparing conventional and organic farming methods found that soil microbial biomass was enhanced in conventional fields relative to organic fields within heterogeneous landscapes (landscapes with a greater proportion of non-agricultural fields), with the reverse true in homogenous landscapes (landscape with a greater proportion of agricultural fields); a result hypothesised to arise from landscape effects on above-ground organisms cascading to the below-ground community (Flohre et al., 2011). Given the importance of the soil microbial community for ecosystem services, the effect of surrounding landscape heterogeneity on soil microbial biomass, community composition and function deserves greater attention.

In addition to examining the effects of field management and landscape heterogeneity on supporting services, it is important to consider how these factors interact with provisioning services (crop production). It has generally been found that more intensively farmed fields produce greater yields but provide fewer supporting services (Birkhofer et al., 2008; Mäder et al., 2002), i.e. there are trade-offs between supporting and provisioning services (Raudsepp-Hearne et al., 2010). However, it has also been shown that increased yields do not necessarily come at the expense of supporting soil services (Williams and Hedlund, 2013), or that lower intensity farming necessarily reduces yields (Seufert et al., 2012). These studies highlight the importance of considering specific management practices and growing conditions on trade-offs between ecosystem services.

The aim of this study was to compare soil ecosystem services within spring barley (*Hordeum vulgare* L.) fields, leys and permanent pastures, and if the services were affected by surrounding landscape heterogeneity (measured at three spatial scales: 100 m, 500 m and 1000 m radii). We did this by measuring and comparing a range of soil physical, chemical and biological properties (indicators of supporting soil services) within barley fields, leys and permanent pastures across a landscape heterogeneity gradient in southern Sweden. Specifically, we measured SOC, TN, plant-available P and water holding capacity (WHC) (indicators of carbon storage, nutrient and water retention); net N mineralisation (indicator of nutrient cycling); microbial biomass (indicator of nutrient cycling and retention) and microbial community composition. For brevity, these indicators of soil ecosystem services are henceforth referred to simply as ecosystem or soil services. In addition, within the barley fields we also looked for trade-offs between soil services, landscape heterogeneity and crop yield, to examine whether increasing yields (provisioning service) came at the expense of soil function (supporting services). We hypothesised that (1) supporting soil services would be greater in permanent pastures than barley fields and leys, and in turn would be greater in leys than barley fields; (2) landscape heterogeneity would have no effect on soil ecosystem services or microbial community composition; and (3) trade-offs would exist between supporting soil services and increasing barley yield, i.e. increasing yield would come at the expense of supporting soil services.

2. Materials and methods

2.1. Site selection and sampling

The study was conducted in Skåne, southern Sweden. The climate is oceanic, with 600 mm average annual precipitation. Farms were selected for sampling based on their surrounding landscape heterogeneity, following a previously published protocol (Rusch et al., 2013; Williams and Hedlund, 2013). This was calculated using scripts developed in MATLAB 7.11.0 on data from the Swedish Board of Agriculture's Integrated Administrative and Control System database. Landscape heterogeneity was described by the combination of the amount of permanent pasture and field border within 1000 m radius landscapes placed over the centre of each farm. The amount of permanent pasture and field border was expressed as proportions of the total agricultural area within each landscape. The proportions of permanent pasture and field border were then combined by extracting the first principal component (PC1) from a principal component analysis (PCA) of the two variables. To ensure that landscapes varied more along PC1 than PC2, all landscapes that had a standard deviation along PC2 greater than one were excluded. To ensure we only worked in predominantly agricultural areas, all landscapes that contained less than 40% farmland were also excluded. All remaining conventionally managed farms were then plotted against PC1 so that as large variation in landscape heterogeneity as possible could be sampled (higher values of PC1 indicate more heterogeneous landscapes – greater area of permanent pasture and field border; lower values indicate homogenous landscapes – smaller area of permanent pasture and field border).