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Review

A Functional Land Management conceptual framework under soil drainage and land use scenarios

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ABSTRACT

Agricultural soils offer multiple soil functions, which contribute to a range of ecosystem services, and the demand for the primary production function is expected to increase with a growing world population. Other key functions on agricultural land have been identified as water purification, carbon sequestration, habitat biodiversity and nutrient cycling, which all need to be considered for sustainable intensification. All soils perform all functions simultaneously, but the variation in the capacity of soils to supply these functions is reviewed in terms of defined land use types (arable, bio-energy, broadleaf forest, coniferous forest, managed grassland, other grassland and Natura 2000) and extended to include the influence of soil drainage characteristics (well, moderately/imperfect, poor and peat). This latter consideration is particularly important in the European Atlantic pedo-climatic zone; the spatial scale of this review. This review develops a conceptual framework on the multi-functional capacity of soils, termed Functional Land Management, to facilitate the effective design and assessment of agri-environmental policies. A final functional soil matrix is presented as an approach to show the consequential changes to the capacity of the five soil functions associated with land use change on soils with contrasting drainage characteristics. Where policy prioritises the enhancement of particular functions, the matrix indicates the potential trade-offs for individual functions or the overall impact on the multi-functional capacity of soil. The conceptual framework is also applied by land use area in a case study, using the Republic of Ireland as an example, to show how the principle of multi-functional land use planning can be readily implemented.

1. Introduction

Sustainable intensification is necessary to respond to the need for global food security so that increased food production can be achieved in an environmentally sustainable manner (Lal, 2009; Benton et al., 2011; Schulte et al., 2014). The Food and Agriculture Organisation (FAO) of the United Nations suggests that primary food production will need to increase by as much as 60% by 2050 to meet the needs of a rapidly increasing global population (Alexandratos and Bruinsma, 2012; McBratney et al., 2014). The soil resource occupies a central role in primary production, which is reliant on effective, tailored planning and land management policies.

In tandem with achieving primary production goals (which includes fibre and fuel provision as well as food production), dual purpose agri-environmental policies must ensure that soils are managed to achieve environmental targets in a socially acceptable and economically viable manner. Within the European Union (EU), for example, environmental targets are set under current European legislation on water quality (Schulte et al., 2010), greenhouse gas emissions (Schulte and Lanigan, 2011) and ecological protection (Schulte et al., 2014). By definition, sustainable intensification requires that any emphasis placed on increasing primary productivity is matched with an equal emphasis on sustainability to enable the delivery of food and ecosystem services into the future (Garnett and Godfray, 2012). Policies by the European Commission such as the Green Infrastructure Strategy and "greening measures" in the reformed Common Agriculture Policy (CAP; European Commission 2014) demonstrate that strengthening of ecosystem services is integral to achieving sustainable intensification. It is anticipated that the Functional Land Management (FLM) framework will support the more effective use of landscape specific agri-environmental policies, such as those considered within the document "Transforming our world: the

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2030 agenda for sustainable development" by the United Nations (2015), rather than the application of uniform measures (such as those in the Nitrates Directive) across diverse farming regions (Bouma et al., 2012; Pacini et al., 2015). The importance of tailored land management policies will become even more prominent in the EU due to the crop diversification measure under the CAP (Mahy et al., 2015).

A spectrum of soil based ecosystems services, which are referred to as soil functions, have been identified in a number of studies and comprise of; supporting, provisioning, regulating and cultural services (Blum et al., 2004; Bouma and Droogers, 2007; Haygarth and Ritz, 2009; Breure et al., 2012; Pulleman et al., 2012; Dominati et al., 2014; Horrocks et al., 2014). Schulte et al. (2014) identified the following five soil functions as key, specifically, for agricultural land use;

1) Production of food, fibre and (bio)fuel, which is a provisioning service. This is the primary function in the agricultural sector.
2) Water purification, which is a regulating service. This comprises the soil's capacity for storage, filtration and transformation.
3) Carbon sequestration.
4) Soil as a habitat for biodiversity and a gene pool.
5) Recycling of (external) nutrients/agro-chemicals, which is a supporting service.

The key to achieving all of these multiple demands on the soil through agri-environmental policy is to understand the intrinsic nature of the soil in order to get the most out of the system sustainably. However, soils vary in their relative capacity to deliver multiple soil functions, owing to the heterogeneous nature of soil, the type of land use and management practices (Haygarth and Ritz, 2009; McBratney et al., 2014; Schulte et al., 2014). Understanding how individual soil properties relate to the functional capacity of a soil has been the basis of much research (Sauer et al., 2011; Breure et al., 2012; Pulleman et al., 2012; Dominati et al., 2014) but less so on a comprehensive view of the interrelationships between soil properties and the full suite of soil functions. To optimise the delivery of individual soil functions, or to maximise the suite of soil functions, requires an understanding of the expected delivery of soil functions as influenced by key soil properties under different land management regimes, as well as the effect that incentivising one function has on the delivery of the other soil functions. Therefore, an integrated framework is required to consolidate the intricacies of such complex multi-faceted information in a simplified, transparent and coherent manner to support the design of a tailored land use policy.

1.1. Objectives

In a previous study, Schulte et al. (2014) related soils' functions to land use but emphasised the need to extend this to include soil type. Therefore, in this paper, the aim was to extend the framework of FLM theory to consider dominant soil type constraints, with two objectives. The first objective was to review the literature to derive concise conceptual models for the interrelationships between land use, soil type and the five aforementioned soil functions of agricultural landscapes. The second objective was to apply these models to build on the initial FLM matrix, which was introduced by Schulte et al. (2014), in order to complete the conceptual matrix of the suites of soil functions. This could subsequently be used to show changes in soil functional capacity in response to policies involving the alteration of land use.

At large spatial scales, these interrelationships are likely to be dependent on, and thus vary between, agro-ecological zones. The scope of this paper is, therefore, limited to the Atlantic climatic zone of Europe, with potential similarities and hence relevance to other temperate maritime climates. Under this climatic regime, excess soil moisture is considered the dominant biophysical constraint to achieving sustainable intensification because of: (a) reductions in herbage yields and growing season, (b) restricted pasture utilisation and trafficability owing to the potential threat of soil compaction, (c) reduced nutrient uptake by plants and (d) nutrient loss to water bodies (Shalloo et al., 2004; Schulte et al., 2005, 2006, 2012; Creamer et al., 2010; Humphreys et al., 2011; O'Sullivan et al., 2015). Based on this, drainage class is used here to encompass key soil properties that represent the soil natural capital, which performs soil functions that contribute to ecosystem services (Calzolari et al., 2016). With respect to climatic change, future strategic planning will need to consider temporal and spatial changes in the soil water balance, which determines land use options and management practices (Rivington et al., 2013).

2. Soil functions and soil management

2.1. Primary productivity

As conceptualised in Fig. 1, primary production is possible under a range of soil moisture conditions and deficits but it varies considerably with the type of land use. Herbage growth in grass pasture is greatest at soil moisture conditions around field capacity, which occur more frequently on moderately drained soils than on poorly drained heavy clays (which may carry water surpluses in excess of field capacity for prolonged periods) (Shalloo et al., 2004; Fitzgerald et al., 2008) or well drained soils that may be prone to (moderate) drought conditions (Laidlaw, 2009; Kroes and Supit, 2011). However, trafficability and herbage utilisation are higher on well drained soils (O'Loughlin et al., 2012; Schulte et al., 2012; Gregory and Nortcliff, 2013).

Most arable crops grow best on well drained soils that have a moisture status beyond field capacity for longer periods throughout the year. However, drought conditions impair plant physiology and limit the transportation of nutrients to the plant roots (Batey, 1988; Briggs and Courtney, 1989; Gardner et al., 1999).

At the other extreme, challenges posed for sensitive plant species on waterlogged soils include poor root development, impaired nutrient uptake (Rechcigl, 1982; Laidlaw, 2009), reduced rates of photosynthesis (Schulte et al., 2012), the production of toxic substances, such as ethylene and methane (Batey, 1988; Briggs and Courtney, 1989; Gardner et al., 1999; Schulte et al., 2012), nitrogen loss by denitrification (Rechcigl, 1982) and increased susceptibility to disease (Rechcigl, 1982; Briggs and Courtney, 1989). Compacted soils are more prone to impeded drainage and saturation, which in turn increases their vulnerability to degradation of the soil structure by livestock and farm machinery (Batey, 1988; Ellis and Mellar, 1995; Schulte et al., 2012; Kuncoro et al., 2014). Alternatively, tolerant species of deciduous and coniferous trees may be selected, in addition to bioenergy crops such as willow (Stolarski et al., 2011), in order to increase primary production on soils prone to saturation.

In summary, moderately drained soils offer the highest capacity for primary production (Ellis and Mellar, 1995). Primary productivity on excessively drained and poorly drained soils tends to be reduced with the exception of some tolerant species of deciduous/coniferous trees and bioenergy crops.

2.2. Water purification

The enrichment of water bodies by residual inorganic plant nutrients, such as nitrogen (N) and phosphorus (P) (Mason, 1998), is a global water quality issue. In general nitrate (NO_3^-) is considered to pose a greater risk to groundwater and transitional water bodies and P to freshwater (Schulte et al., 2006).