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Climate change and soil wetness limitations for agriculture: Spatial risk assessment framework with application to Scotland

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ABSTRACT

Waterlogged soils can act as a major constraint on agriculture by imposing limits on the use of machinery and stocking levels. Inappropriate use of waterlogged soils can cause serious damage to soil and water resources. Limitations are particularly pronounced in locations with wetter climates and on soils which have inherent drainage problems. Constraints may also vary temporally due to climate variability and climate change. These issues are investigated through the strategic use of a risk assessment framework that combines climatic and soil factors to map changes in soil wetness risk at country level. Wetness risk is evaluated in terms of soil wetness classes and the constraints it imposes on arable and improved grassland using an empirical land capability scheme. A case study in Scotland analyses spatio-temporal variations of wetness risk and associated land-use constraints for 1961–1980 and 1991–2010 periods and using a future 2050s projection based upon the HadRM3/HadCM3 climate model ensemble. Results suggest increased risk levels in recent decades for south-west and central Scotland which are both important areas for livestock agriculture. However, wetness risk in these high risk areas is tentatively projected to reduce under average 2050s conditions based upon a central estimate from the model ensemble. Wetness risk has been adjusted based upon the assumed presence and performance of subsurface field drainage systems but this remains a significant uncertainty due to limited data availability. As artificial drainage represents the major alternative adaptation strategy compared to change of land use, the case study highlights a need to further evaluate its efficacy and long-term viability for those areas identified at high risk.

1. Introduction

Waterlogged soils occur due to the location-specific interaction of soil and climate variables resulting in saturation of pore space through the soil profile. For wetter locations, the seasonal pattern of waterlogging has a major impact on the viability and management of crops and livestock production (Schulte et al., 2012). Efforts to alleviate these natural constraints have been made through the use of drainage schemes to remove excess water, improve agricultural productivity and maximise use of land resources. Growing pressures on food, energy and water security mean that there is increased need to develop strategies to maximise and sustain the use of finite land resources (Godfray et al., 2010) and to maintain soil security (McBratney et al., 2014). These pressures include both increasing demands on land but also the effects of drivers of change that affect the availability of land to meet those demands, notably climate change (Bakker et al., 2011). The objective of the present study was to develop and apply a risk assessment framework to investigate the changing role of climate in soil wetness problems, and, by using a land evaluation approach, to facilitate strategic risk management of land and soil resources at national scale. Land evaluation and land capability classification provide strategic tools to assess and utilise land resources based upon standard criteria including the use of soils and climate data (Bagheri Bodaghabadi et al., 2015; FAO, 2007; Manna et al., 2009). By comparing intrinsic capability, as defined by a reference classification, against current condition as influenced by management practices, important information can also be obtained on soil security issues which, when codified, can inform policy development (Bouma et al., 2012; McBratney et al., 2014).

The moisture content of a soil has an effect on its consistency, strength and vulnerability to deformation. Wet soils with low bulk strength that exceed Atterberg's limit for plasticity become more prone to compaction by machinery or livestock, or to smearing due to excessive shear forces which breaks soil continuity (Droogers et al., 1996; Hamza and Anderson, 2005). The resulting damage to soil structure can reduce infiltration rates and hinder drainage causing increased surface runoff and erosion, whilst compaction can also reduce rooting depths and hence plant growth (Ball et al., 1997). Excess wetness will also mean that machinery will sink into the soil and wheel slip will occur which constrains management practices. The annual cycle of moisture conditions in the soil therefore defines the soil water regime of a location and the duration of waterlogged soils can be the key influence on the viability and scheduling of farm activities at that site (Schulte et al., 2012). For example, soils with a water table at <70 cm

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depth for four to seven months of the year have been identified as being at higher risk of compaction under vehicle traffic or livestock (Robson and Thomasson, 1977).

Soil wetness constraints mean that effective risk management is crucial to ensure farm productivity and to avoid long-term damage to the soil resource. In terms of arable use and management, risks are manifest through *workability* constraints on tillage or harvesting, or on general *trafficability* access by machinery (Earl, 1996; Rounsevell, 1993). For improved grassland, general trafficability constraints act in combination with potential livestock poaching risks from damage caused by animal hooves to soil and vegetation (Piwowarczyk et al., 2011). Wetness constraints may mean that crops are unviable, or that livestock have to be kept indoors longer during the wetter part of the year or that stocking rates are lower, each of which has an impact on farm economics (Shalloo et al., 2004). Poaching damage is a common problem in areas where winters are relatively mild with a longer growing season and farmers aim to maximise grazing of livestock in fields rather than for them to be managed and fed indoors (Tuohy et al., 2014). Neglecting these constraints can cause long-term problems: for example, soil compaction due to tractor traffic has been estimated to reduce yields by an average of 10% (Mosquera-Losada et al., 2007).

Field drainage systems are designed to remove excess water and lower the water table providing better working and productivity conditions for the soil. For intensive agriculture (arable and grassland), underdrainage systems below the soil surface are most commonly employed (usually via pipes or tiles) to avoid disruption to the continuity of field systems that are optimised for efficient cultivation or livestock grazing. Drainage of wet ground has been reported to increase yields of a wide range of crops by 10–25% (Castle et al., 1984). Similarly, analysis of annual grass productivity has suggested that well-drained soils improve yield by 1.25–3.55 t/ha compared to poorly-drained soils in the same climatic conditions (Fitzgerald et al., 2005). However, the hydraulic performance of drainage systems has been shown to be sensitive to changing climatic parameters dependent on their design (Armstrong et al., 1995).

Soil water regimes can be recorded in the field using dipwells or borehole monitoring (e.g. Lilly, 1995, 1999) but this can be prohibitively costly to apply on a larger scale. As an alternative, simulation modelling can be employed to improve understanding of agricultural, pedological and hydrological processes at field to region scale (e.g. Sloan et al., 2016; Droogers and Bouma, 2014), but obtaining robust parameter and validation data can also be resource-intensive if existing monitoring data is not available. This identifies a need for a more strategic approach as developed through the use of pedotransfer functions to link empirical data and soil properties, together with the mapping of soil wetness or soil drainage classes based upon these relationships (Hollis et al., 2014; Lilly and Matthews, 1994). A strategic approach can also enhance stakeholder engagement when linked to land evaluation, including the potential to integrate mapping and simulation data within the same framework. Soil wetness properties can be linked to land use constraints based upon empirical data by modelling the seasonal soil water regime and its influence on agricultural 'working days' or stocking rates during the year (Piwowarczyk et al., 2011; Rounsevell and Jones, 1993).

Excess soil wetness has been identified as the primary constraint on agricultural land use for the Atlantic climatic zones of North-west Europe (Schulte et al., 2012). Following over 200 years of investment in land remediation for agricultural improvement, Britain and Ireland have been identified as the most extensively underdrained region of Europe, and probably the world (Robinson and Armstrong, 1988). A case study is presented from Scotland where approximately 25% of the land area is under regular cultivation as either arable land or improved grassland (Suppl. Mat. Fig. S1) but where grants for drainage were phased out in the late 1980s. Variations in soil moisture from year to year show wetter years tend to result in lower crop yields indicating that wetness is a primary climatic constraint in Scotland (Brown, 2013). Estimates of the total area of land drained from 1946 to 1979 vary between ca. 250,000–350,000 ha including a small proportion for arterial drainage systems (Green, 1979; Robinson et al., 1990). Drainage was typically small-scale based upon traditional local practices (Armstrong et al., 1992) and therefore did not involve detailed soil physical investigations or larger-scale systematic interventions that have occurred in some other countries (e.g. Netherlands). Underdrainage is particularly important in Scotland because the general wetness of the climate acts against efficient opportunities to employ subsoiling operations used elsewhere to loosen or shatter the soil and improve drainage properties. The most common reason for requiring drainage has been on soil profiles formed on glacial tills where slowly permeable layers occur due to illuviation of fine-grained material and relatively high rainfall rates; the resulting perched water table therefore causes increased frequency of soil saturation close to the surface (Morris and Shipley, 1986). Depth to a slowly permeable layer is therefore a prominent feature of the wetness risk assessment developed in the present study. In addition, underdrainage has been used to address problems due to high groundwater tables or adjacency to spring and seepage lines but these tend to be more localised issues requiring a detailed topographic or hydrogeological investigation beyond the strategic evaluation presented here.

Previous work using an updated method of land capability assessment for agriculture in Scotland has shown the influence of climatic warming as beneficial for both the more productive land and more marginal areas, albeit with potential increased drought risk for some locations in the future (Brown et al., 2008, 2011). However, the influence of soil-climate interactions on wetness risks through changes in seasonal soil water regimes have yet to be fully evaluated. In addition, implications of wetness risks for soil security, land use decisions and climate change adaptation planning have yet to be formulated.

2. Methods

The methodology for risk assessment follows the convention that risk is defined by the combination of inherent susceptibility (or *vulnerability*) of a system to damage and its *exposure* to conditions that could cause that damage (Calow, 1998). The same logic has previously been applied for agricultural drought risk combining soil properties with climatic exposure (Brown et al., 2011). For wetness risk, the potential for soil structural damage is therefore evaluated based upon: (i) intrinsic soil vulnerability properties that determine the strength and plasticity of the topsoil together with soil profile variations that control drainage; (ii) the frequency of wet conditions in the climate regime. The general procedure to integrate soil and climate data is summarised in Fig. 1. Land-use constraints have been adapted from the official land classification system employed in Scotland which has a strong empirical grounding and a widespread familiarity due to its broad user base (Bibby et al., 1982; Brown et al., 2008). As explained below, modifications have been made to better incorporate knowledge of associations between soil profiles and soil water regime, and to integrate digital spatial data, whilst retaining the same classification principles. All datasets were integrated on a 1 km grid using the ARCGIS10 system. As the method is intended for large-scale strategic assessment of trafficability, workability and poaching constraints, the local role of topography in influencing lateral flows and drainage rates is not considered further here, nor is the potential impact of climatic wetness on plant physiology and yield potential as this forms a component of a general land capability assessment previously completed (Brown et al., 2008). Risk assessment is applied both for past climate change, comparing 1961–1980 and 1991–2010 periods, and for future climate change focussed on a 2050s projection.

2.1. Soil and climate data

Soils data were derived from the Soil Survey of Scotland which systematically described and collated soil profiles and survey records to characterize a unique set of soil series for the country that formed the basis of soil mapping units. Digital polygon data at 1:250,000 scale