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.

Keywords: soil moisture, soil waterlogging, field drainage, land capability, land suitability, adaptation strategies

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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 (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 less than 70 cm 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 1.25-3.55t/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. Figure 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 1946-1979 vary between ca. 250,000-350,000ha including a small proportion for arterial drainage systems (Green, 1979; Robinson et al., 1990). Drainage was typically small-scale based upon traditional local practises (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 Figure 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 1km 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 (minimum size of map unit ca.75ha) were converted to a 1km grid based upon the series with the largest areal extent in each grid cell and the cell attributed with the type profile data for that series. Although this gridding procedure caused some generalization of soils data it was considered suitable for a large-scale strategic assessment.

Observed climate data for 1961-2011 were available from the gridded datasets produced by the UK Met Office (UKMO) for as a 5km monthly climatology interpolated from station data using a regression procedure (Perry and Hollis, 2005). These data were used to derive a water balance for each grid cell by calculating a soil moisture deficit for those times during the year when potential evapotranspiration (PET) exceeded precipitation, following previously established procedures for land capability (Brown et al., 2008). Soil moisture deficit provides a reliable indicator of seasonal variations in the soil water regime relative to a zero deficit condition when the soil is totally saturated and defined as being at field capacity (Kerebel et al., 2013; Premrov et al., 2010). PET was calculated from UKMO climate data (maximum temperature, minimum temperature net radiation, relative humidity, wind speed) according to the FAO56 method with sunshine duration used to estimate net radiation values (Allen et al. 1994; Pereira et al., 2015). Due to the absence of wind data for the Northern Isles before 1971, PET data (and long-term averages) could only be calculated post-1970 for this small area.

Future climate data for calculating soil moisture in the same way were derived from the HadRM3/HadCM3 model suite which is used both for IPCC assessments and the UK Climate Projections 2009 (UKCP09: Murphy et al., 2009). The suite provided a higher-resolution (25km) Regional Climate Model (RCM) for NW Europe (HadRM3) that was nested within the boundary conditions of the Global Climate Model (GCM), both being run as a perturbed physics ensemble (PPE) with differing variable values for key parameters to include model uncertainty. Data were extracted for the UKCP09 Medium Emissions (IPCC A1B) scenario and for the purposes of the assessment the mean ensemble value was calculated for the relevant climate parameters to provide a central estimate of future climate change for the 2050s period. Data were also obtained for the standard baseline period (1961-1990) and the change factors between the future mean and baseline periods calculated. These change factors were then used to further downscale the future data to the same resolution (5km) as the observed data by interpolating the changes onto the same UKMO monthly climatology (Perry and Hollis, 2005). This procedure (delta change method) acts to remove significant biases in the raw model data (Wilby et al., 2009).

2.2 Wetness Risk Assessment

The influence of climate change is evaluated through an assessment of both soil wetness classes and land capability. Soil wetness classes (in some countries analogous to soil drainage classes) represent a familiar and commonly used expedient employed by soil surveyors to characterise the soil water regime of a location: in the UK they are used to indicate the average annual duration of waterlogging in the soil profile (Lilly and Matthews, 1994). Land capability assessment is based upon relationships between soil water regime and land use flexibility derived by the national Soil Survey (Bibby et al., 1982).

Soil constraints for both arable cultivation and improved grassland were defined by topsoil water retention and depth to a slowly permeable layer; these constraints were integrated into a vulnerability index from 1 (low) to 6 (high) that was applied for each soil mapping unit (Table 1).

Topsoil water retention (A and O horizons) was summarised through three categories based upon soil texture data (Table 2) and defined according to the volume of water held by an undisturbed core sample equilibrated at 5kPa suction (Hall et al., 1977). The presence of and depth to a slowly permeable layer provides a key measure of soil drainage characteristics. In physical terms, a slowly permeable layer has been defined by a saturated lateral hydraulic conductivity of less than 10cm/day, but its presence may also be deduced from morphological criteria (texture and structure) in the soil profile. Depth to a slowly permeable layer is generally considered a more reliable indicator of soil drainage properties than the presence at a particular depth of gleying (grey, grey-blue, or ochreous mottling of soil colour due to reduction of iron compounds under anaerobic conditions). Gley morphology can be recorded through the presence of common or many mottles in the profile as distinguished from the soil matrix through the diagnostic use of Munsell colour charts to help distinguish waterlogged gleying from colours inherited due to parent material (van Breemen and Buurman, 2002). Although gleying is indicative of intermittent waterlogging, it may be an unreliable indicator of the soil water regime by itself due to the influence of other factors (e.g. presence of organic matter) or because it is a relict feature (Lilly and Matthews, 1994). For the present study, representative data for both depth to slowly permeable layer and gleying were available for those soil series where such features are present; these data were used together and in the rare case of significant differences, the deeper depth was used.

The key climate parameter was summarised as the number of days during the year when soils are notionally at field capacity as calculated through the water balance assessment. Field capacity has been broadly defined as "the amount of water remaining in soil two or three days after having been wetted and after free drainage is negligible" (SSSA 1984). Although the concept of field capacity has been criticised due to local variations and difficulties in demonstrating when equilibrium conditions are reached (Cavazza et al., 2007), it has strategic value in providing a consistent relative measure of saturated conditions in a spatial and temporal context for land evaluation. As a soil attribute, field capacity can be measured in the laboratory using a reference suction value (typically 10mb is used to define a ‘wet’ soil in the UK) but the present study uses a meteorological definition, hence the period at field capacity was inferred to be when potential soil moisture deficit was at 0mm. Typically soil moisture deficits increase during the summer months, as PET rates are higher and rainfall rates are lower, to reach a maximum deficit value before decreasing towards the autumn or winter as colder wetter conditions return. Depending on location in Scotland, the period at field capacity may extend for much of the year in the wetter areas or be limited to only the winter months in the drier areas which have relatively high soil moisture deficits (Brown et al., 2008). With the exception of some locations in anomalous dry winters, all locations in Scotland return to field capacity during the winter months.

The definition of soil wetness classes used by Bibby et al. (1982) was based upon the presence and depth of gleying. However, the unreliability of gleying to indicate the current soil water regime have led to a refined classification based predominantly upon depth to a slowly permeable layer in combination with the period at field capacity (Jarvis et al., 1984; Lilly and Matthews, 1994); this refinement has been followed by the present study (Table 3).

Assessment of wetness risks for land use was distinguished between those for arable cultivation (workability and trafficability constraints) and those for improved grassland (trafficability and poaching constraints). The risk assessment combined the data previously produced using the soil vulnerability index (Table 1) with the level of exposure to climate wetness, based upon the original schema of Bibby et al. (1982) and further adjustments for consistency with actual land use patterns. Suitability for arable cultivation (Table 4) and improved grassland (Table 5) were therefore defined using different levels of constraint. Bibby et al. (1982) had used the average maximum potential soil moisture deficit to define constraints for improved grassland (following Harrod, 1979) but this value is more indicative of dry summer conditions rather than exposure to climatic wetness, hence the use in Table 5 of field capacity days as the climatic constraint. A further modification to the original Bibby et al. (1982) schema was to identify an upper limit for field capacity days beyond which the specified land use was unsuited regardless of soil type; this was set at 240 days for arable and 270 days for improved grassland based upon field evidence.

2.3 Incorporation of Field Drainage

Soil profile data representative of natural drainage properties may not adequately represent the modified drainage properties of improved agricultural land. This is particularly relevant for soils that have a slowly permeable layer but only weakly-expressed gley morphology as the presence of artificial improved drainage has reduced the intrinsic soil constraints and the level of waterlogging. Previous research in the UK has noted this discrepancy and suggested that such soils should be represented by a soil wetness class that is one class higher than the depth to slowly permeable layer would normally indicate (Jarvis et al., 1984; Lilly and Matthews, 1994). Unfortunately, despite the widespread use of field drainage for improved agricultural land in Scotland, information on the location of underdrained land in Scotland has not been systematically collated and historical records are incomplete (Anthony et al., 2012; Green, 1979; Lilly et al., 2012; Mackay, 1973;; Robinson et al, 1990). However, at national scale it is possible to infer, based upon land use and natural soil properties, those soil types that have been substantially modified by underdrainage due to problems with perched water tables. Hence, for the present study, soils described by the Soil Survey as ‘brown soils with gleying’ (dystric/eutric stagnic cambisolss) and ‘non-calcareous surface-water gleys’ (dystric/eutric mollic/umbric stagnosols) were both assumed to have artificial drainage which concurs with their predominant use for improved agriculture (Lilly et al., 2012). Data on the influence of underdrainage on these two soil types is very limited and this also suggests that the age and type of the drainage system can also have an important effect (Lilly, 1999; Robinson, 1990). Therefore a general approach was taken to modify the intrinsic wetness vulnerability index of these two soil types by increasing the typical depth to the water table (as represented by the slowly permeable layer) by 20cm. This value was based upon a review by Robinson (1990) that suggested typical lowering of water tables of 10-40cm due to underdrainage.

Greater lowering values are typically associated with active use of subsoiling management actvities, which are much less practised in Scotland, and smaller values are representative of impeded permeability in clay-rich soils which are not found in Scotland, hence a value of 20cm was chosen as representative. This order of magnitude of adjustment is also consistent with modifications made to soil wetness classes when it is assumed underdrainage has modified natural soil properties (Jarvis et al., 1984; Lilly and Matthews, 1994). The area covered by this adjustment and assumed to have active field underdrainage is 14,624km^2 (Suppl. Mat. Figure S2); other areas and soil types may also have drainage systems but as discussed later they have a lesser bearing on the implications for land use at national scale.

3. Results

Mapping of soil properties using the wetness vulnerability index shows the diversity of intrinsic natural constraints that exist in Scotland (Figure 2). In general, eastern districts tend to have less vulnerable soils, partly due to the presence of coarser-grained parent material but in addition lowland areas with naturally impeded drainage are assumed to be underdrained consistent with the predominance of intensive agricultural systems. Western districts typically have more fundamental limitations, notably due to the presence of organic and peat soils with high water retention. However, lowland areas of south-west Scotland and central Scotland have a lesser vulnerability although this is abetted by underdrainage in many locations (Suppl. Mat. Figure S2) to counteract natural limitations due to a relatively shallow slowly permeable layer (typically at 20-40cm depth). It should be noted that Figure2 also includes poorly-developed or skeletal soils in the uplands which, although considered of lower vulnerability based upon wetness criteria, have other fundamental limitations for agricultural capability (e.g. shallow depth, stoniness, nutrient availability).

With regard to climatic constraints, there are also important regional variations in the period when soils are inferred to be at field capacity (Figure 3). Due to the wetter climate in west Scotland, the general inference is for a longer period at field capacity when compared to drier eastern districts, although with local variations. By comparing 1991-2010 with the baseline period of 1961-1980 it can be seen that, although the general west-east pattern is similar, there has been a shift to wetter conditions in south-west and central Scotland districts with typically 20-30 days longer at field capacity each year. The changes in eastern Scotland over these two periods are more variable with some districts having less average time at field capacity, notably areas of south-east Scotland, whereas other areas have longer time at field capacity, notably in some locations in north-east Scotland where the average period at field capacity has extended by 10 days or more. The future 2050s projection shows that large areas of east Scotland and some parts of south-west Scotland have less days at field capacity (ca. 20-30 days), but large areas of west Scotland continue to be wet for much of the year (Suppl. Mat. Figure S3).

The interaction between soil vulnerability and climatic wetness can be summarised in terms of wetness classes (Figure 4). In general, the presence of free-draining soils and shorter periods at field capacity mean that many lowland areas of eastern Scotland are wetness class I or II. By contrast, western Scotland has a combination of longer periods at field capacity and poorer-draining soils which result in a higher wetness class, with the exception of areas of free-draining soils notably in south-west Scotland. The interaction of soils and climate can be highlighted in central Scotland where the Balrownie soil series, described as consisting dominantly of 'brown earths with weak gleying' (dystric/eutric stagnic cambisols) and a depth to a slowly permeable layer greater than 40cm, extends from west to east across the country: these soils vary in wetness class from IV to II across this west-east transect due to the transition from wetter to drier climate. Comparing the periods 1991-2010 to 1961-80 indicates that some parts of eastern and south-east Scotland have actually improved in class (III to II, or II to I) due to a reduction in days at field capacity. For the same comparison, areas of south-west Scotland are shown to have a reduction in wetness class (IV to V) due to an increase in days at field capacity. However, the future 2050s projection (Figure 4c) suggests that the reduction in wetness class in vulnerable parts of the south-west may be reversed (V to IV) and also that many areas in the east could see a further improvement in class (notably III to II).

Finally, the implications for changes in land capability can be evaluated (Table 6). For arable land (Figure 5) the general distinction is between land that is suitable or very suitable in lowland eastern Scotland compared to being marginal or unsuitable in western Scotland with the exception of small areas of low vulnerability soils. In terms of recent changes, comparing 1991-2010 against 1961-1980 shows an overall increase in the area of land unsuitable for arable (by ca.5%) with the main areas affected being south-west and central Scotland (locations becoming marginal or unsuitable) and the far north Scotland (locations becoming unsuitable). In addition, a slight downgrading of some of the land in north-east Scotland from very suitable to suitable may be noted for the same comparison. For improved grassland (Figure6), a larger proportion of south-west Scotland is identified as suitable or very suitable compared to arable; these are presently important areas for livestock production. Overall there is apparently only small changes between the two past periods but Figure 6 indicates that for 1991-2010 some of the suitable land in south-west Scotland is re-classed as 'marginal' indicating the consequences of increased climatic wetness in these areas on vulnerable soils. Large areas of eastern Scotland remain suitable or very suitable for improved grassland for both these periods but some land in north Scotland decreases from very suitable to suitable. The future 2050s projections shows continued or improved suitability for both arable and improved grassland (Table 6): this is particularly apparent for east Scotland but there is also a suggestion that the decline in suitability for areas of south-west Scotland for the most recent observed period (1991-2010) may be reversed (Figures 5c and 6c), although for reasons discussed below this must be regarded as a tentative inference at present.

4. Discussion

4.1 Refining the risk assessment

The risk assessment framework facilitated identification of both spatial and temporal relationships between wetness risk and land use in Scotland. Strategic-level mapping based upon this framework has distinguished low risk and high risk areas based upon the combination of soil and climate factors. Investigating soil-climate relationships in a temporal context shows that although many areas remain either low or high risk, some areas are inferred to have experienced important changes in risk due to a changing climate. In particular, the case study has identified a recent increase in wetness risk for areas of south-west and central Scotland. This also concurs with anecdotal evidence from the farming community of increased management problems in these areas. An increase in precipitation rates over western regions of Britain in the 1991-2010 period may be associated with an increased prevalence of westerly atmospheric circulation in the North Atlantic and elevated exposure to wetter conditions in these locations (Fowler and Kilsby, 2002; Sutton and Dong, 2012).

Results from the future 2050s projection would suggest that wetness risks may decrease by this time period for large areas of Scotland (except the north-west and uplands), although this requires further substantiation. Despite the use of RCMs, climate models have considerable uncertainties when modelling local precipitation patterns and have only limited skill in simulating recent patterns of change (Wilby et al., 2009). The results here are based upon a central (mean) estimate from the HadRM3/HadCM3 ensemble but extreme members of this ensemble or the use of other climate models differ in terms of the magnitude of expected changes, suggesting further analysis is required. The projected future reduction in days at field capacity is largely attributable to a longer time taken to return to field capacity in autumn/winter due to an average trend towards drier summers and larger soil moisture deficits for the UK (Brown et al., 2011) but this will have important local variations and is also likely to include significant variability in conditions from year to year (Sexton et al., 2015).

The main value of the risk assessment is therefore to identify priority locations for more detailed monitoring and analysis. This more detailed work should include local-region scale simulation modelling of soil hydrological processes (e.g. Sloan et al., 2016) and the interaction of soil and climate constraints on specific land use practices linked to workability, trafficability or poaching risks (e.g. Cooper et al., 1997; Fitzgerald et al., 2008). Local-level risk assessment would also incorporate the influence of topography by using data from digital terrain models to develop finer-resolution risk maps based upon recent advances in soil mapping (Miller and Schaetzl, 2016; Minasny and McBratney, 2016) including interpolation of soil profile data linked to hydrological properties (e.g. Baggaley et al., 2009; Campling et al., 2002; Zhao et al., 2014). It may also include further assessment of the complex interactions between soil and climate in a land use context, such as the potential for frost to reduce liquid soil moisture contents and provide improved support for machinery (Cooper et al., 1997). The increased availability of soil moisture data from remote sensing sources also allows the possibility to further validate the risk assessment at an operation level linked to dynamic changes in the soil water regime across different soil types (e.g. Niang et al., 2012). Systematic analysis of wetness constraints, including dynamic simulation data, can be also compared with other influences on land capability in a changing climate including drought risk (Brown et al., 2008, 2011) to develop targeted initiatives to enhance soil security.

Temporal changes in wetness risk may cross thresholds that imply existing land uses are unsustainable unless remedial actions are taken to improve risk management. An increased prevalence of wetter conditions in high risk areas will exacerbate problems such as soil compaction and erosion, counteracting any potential gains from a warming climatic due to a longer growing season. Wetness risk is also manifest through a range of related issues for evaluating land use options and soil security, suggesting that further progress could be made towards an integrated risk assessment including climate change. These related issues includes the consequences for water quality due to increased runoff rates, and to carbon storage and greenhouse gas emissions, which are linked to nutrient availability and fertiliser applications, and potentially compounded by soil compaction problems (Coyle et al., 2016; Dunn et al., 2012; Kerebel et al., 2013; Lilly et al., 2009; Sloan et al., 2016). Soil wetness is also known to elevate the risk from some plant and livestock diseases, notably the prevalence of liver fluke (*Fasciola hepatica*) in livestock areas (Fox et al., 2011).

Risk assessment can therefore distinguish between the intrinsic capability of soils and their current condition assessed against multiple criteria for maintaining sustainable soil, water and land resources , recognising that some soils are particularly sensitive and vulnerable (McBratney et al., 2014) .In this context, the use of an intrinsic soil vulnerability index in the present study has some similarities to the development of the Hydrology of Soil Types (HOST) classification as used for water quality, flooding and base flow studies (Boorman et al., 1995; Schneider et al., 2007), although HOST classes do not include artificial drainage.

4.2 Implications for land use

In a policy context, the use of agroclimatic criteria to delimit natural handicaps on land use is particularly relevant in terms of discussions to use such criteria to define locations for subsidy support under the European Union 'Areas of Natural Constraint' scheme (replacingr the previous Lesser Favoured Areas (LFA) scheme). Schulte et al. (2012) make the case for including wetness constraints based upon annual field capacity days in ANC/LFA definition for Atlantic regions in addition to aridity constraints for southern Europe. Following Fitzgerald et al. (2005), Schulte et al. (2012) suggested that locations with 80% of years above a threshold of 220-230 days at field capacity would likely to be unsustainable for improved grassland systems based upon herbage availability. The present study has used an approach based upon average (mean) field capacity days in combination with soil vulnerability types but the results are similar. The upper limits for arable suitability (240 mean days) and improved grassland suitability (270 mean days) identify that even on free-draining soils, which may allow access to land during the field capacity period after one or two rain-free days, there are limits to drainage ability and therefore the likelihood of saturated conditions. More detailed local work using soil hydraulic properties and daily climatological data could be used to identify local limits. Further work on thresholds for risk management would also benefit from investigation of inter-annual variability to define probabilities of exceeding threshold values. Previous work based upon land capability assessment has identified that western Scotland experiences greater inter-annual variability of land quality compared to eastern Scotland and notably that this variability has increased in recent decades for south-west Scotland (Brown and Castellazzi, 2015). This increased variability implies an increased risk of poorer wetter years occurring in addition to drier years which makes farm planning difficult and can cause particularly severe problems during run of consecutive wetter years.

4.3 Implications for drainage systems

A critical assumption and major uncertainty in the present study is the presence and performance of field underdrainage in vulnerable areas, notably in south-west and central Scotland due to wetter conditions. The extensive but small-scale development of field drainage systems in Scotland meant they were implemented mainly following local tradition rather than a systematic use of science and engineering (Morris and Shipley, 1986; Robinson et al., 1990). Comparison of new against old drainage systems at adjacent sites in central Scotland has found that the site with the modern drainage system had a water table within 30 cm of the soil surface for only 31% of the time while the site with the older drainage system had a water table at this height 68% of the time (Lilly, 1995). Maintenance of drainage systems has not been a policy priority in Scotland and the scientific community has focussed on smaller-scale studies because of limited data availability. As the effective lifespan for underdrainage systems is estimated ‘conservatively’ as being 50 years (Green, 1979) then current functioning of many systems can be realistically assumed to be sub-optimal (Anthony et al., 2012). A small survey on arable mineral soils has suggested that local farmers considered their drainage systems were in ‘moderate’ (71%) or ‘good’ (29%) condition (none suggested ‘excellent’ or ‘poor’) but that several noted a decline in performance in recent years

(Lilly et al., 2012).Further survey and analysis is therefore required to better understand the role of underdrainage in high risk areas.. The availability of more data on water table dynamics (e.g. from dipwells or remote sensing) would also facilitate greater use of inverse modelling techniques to identify local soil properties and hence capability mapping.

If renewed drainage work is not undertaken, based either on economic or environmental considerations (e.g. implications for water quality), then the main adaptation alternative is a change in land use, either towards more extensive agriculture (e.g. rough grazing) or other uses such as forestry, which are more suited to the intrinsic soil constraints and capability. In some situations, the potential for agro-forestry as a transitional land use to alleviate drainage problems may be beneficial (Turner and Ward, 2002) although this is currently not a favoured approach in Scotland.

5. Conclusions

A risk assessment framework for soil wetness based upon interaction of soil and climate factors has been developed and applied to a large-scale case study in Scotland to evaluate the role of recent and future climate change. Soil wetness classes show a recent increase in wetness risk for vulnerable soil types in south-west and central Scotland, due to an increase in days when soils are likely to be fully saturated and at field capacity. In terms of land capability, this means that increased workability and trafficability constraints for arable land have reduced the availability of suitable land in these locations, whereas for improved grassland, the same vulnerable soils are inferred to have become more marginal due to soil poaching risks despite their importance for livestock production. Current agricultural practices in these high risk areas may therefore be unviable. However, a central 2050s projection of future change based upon the HadRM3/HadCM3 climate model tentatively suggests that a long-term shift towards drier conditions for more of the year could reduce risks, notably in southern districts. The past and future assessment involves key assumptions regarding the location and performance of field underdrainage systems. It therefore highlights the need for more detailed work on soil wetness and drainage systems in targeted areas to ascertain whether in the long term renewed drainage systems can mitigate changing risk factors or alternatively whether a change in land use may be necessary.

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Table 1. Soil wetness vulnerability index (modified from Bibby et al., 1982)

		Topsoil retained water capacity		
Soil type	**Depth to SPL or gleying**	**Low**	**Medium**	**High**
Mineral	>80	1	1	1
Mineral	60-80	2	2	3
Mineral	40-60	3	3	4
Mineral	<40	4	5	5
Organo-mineral*	<40	-	-	6
Organic & Peat	All	-	-	6

*Humose or peaty topsoil above mineral subsoil

Table 2. Categories for retained water capacity based upon particle size (Bibby et al., 1982)

Retained water capacity (% volume)	Texture classes
High (>45%)	Peaty & humose soils Clay, silty clay, sandy clay Part: clay loam, silty clay loam
Medium (35-45%)	Loam, silt loam, silt, sandy clay loam Part: clay loam, silty clay loam
Low (<35%)	Sandy loam, loamy sand, sand

Table 3. Soil wetness classes based upon an average year: (a) as defined by field conditions; (b) relationship to climate and soil attributes (after Jarvis et al., 1984, Lilly and Matthews, 1994)

(a)

Wetness class	Duration of waterlogging in soil profile
I	Not waterlogged within 70cm depth for more than 30 days
II	Waterlogged within 70cm for 30-90 days
III	Waterlogged within 70cm for 90-180 days
IV	Waterlogged within 70cm for more than 180 days, but not within 40cm depth for more than 180 days
V	Waterlogged within 40cm for 180-335 days and within 70cm for more than 335 days
VI	Waterlogged within 40cm for more than 335 days

(b)

	Depth to slowly permeable layer in gleyed soils					Not gleyed
		<40cm	40-60cm	60-80cm	> 80cm	
Days at Field Capacity	**Peaty soil**	←	**Mineral soils**			→
<100		II	II	II	I	I
100-125		III	III	II	I	I
125-150		III	III	II	I	I
150-175		IV	IV	III	I	I
175-200	V	IV	IV	III	I	I
200-225	VI	V	IV	III	II	I
225-250	VI	V	V	IV	II	I
250-300	VI	V	V	V	III	I
>300	VI	VI	VI	VI	IV	I

Table 4 Workability and trafficability assessment for arable capability (after Bibby, 1982)

	Soil vulnerability class					
Field capacity days	**1**	**2**	**3**	**4**	**5**	**6**
<125	VS	VS	VS	S	S	S
125-150	VS	VS	S	S	S	M
150-175	VS	S	S	S	M	M
175-200	S	S	M	M	M	NS
200-240	S	M	NS	NS	NS	NS
>240	NS	NS	NS	NS	NS	NS

VS: very suitable; S: suitable; M: marginal; NS: not suitable

Table 5. Trafficability and poaching risk for improved grassland capability

	Soil vulnerability class					
Field capacity days	**1**	**2**	**3**	**4**	**5**	**6**
<200	VS	VS	VS	S	M	NS
200-230	VS	S	S	M	NS	NS
230-270	S	S	M	NS	NS	NS
>270	NS	NS	NS	NS	NS	NS

VS: very suitable; S: suitable; M: marginal; NS: not suitable

Table 6. Total area of suitability classes (as %) in Scotland for each time period

	Very Suitable	**Suitable**	**Marginal**	**Unsuitable**
Arable 1961-1980	13.3	12.9	4.6	69.2
Arable 1991-2010	8.5	14.6	2.9	74.0
Arable 2050s	19.6	13.5	8.5	58.4
Improved Grassland 1961-80	26.1	7.6	2.7	63.6
Improved Grassland 1991-2010	22.5	9.1	3.5	64.9
Improved Grassland 2050s	33.3	4.3	2.0	60.4

List of Figures

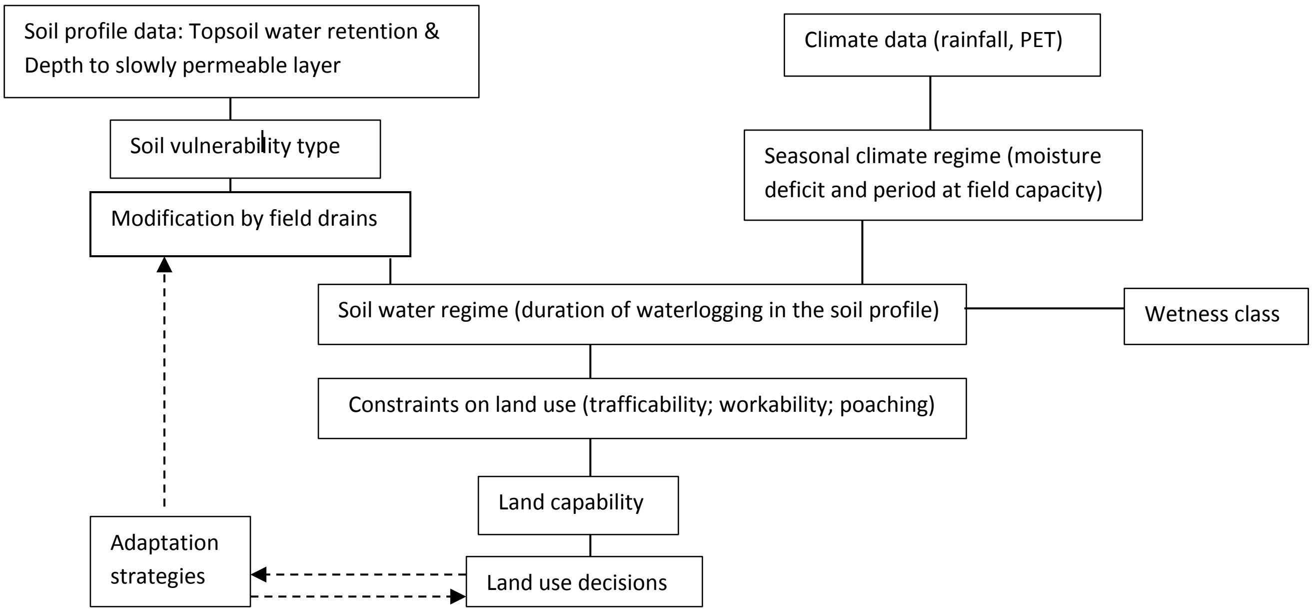

Soil profile data: Topsoil water retention &
Depth to slowly permeable layer
Soil vulnerability type
Modification by field drains
Climate data (rainfall, PET)
Seasonal climate regime (moisture deficit and period at field capacity)
Soil water regime (duration of waterlogging in the soil profile)
Wetness class
Constraints on land use (trafficability; workability; poaching)
Land capability
Adaptation strategies
Land use decisions

Figure 1

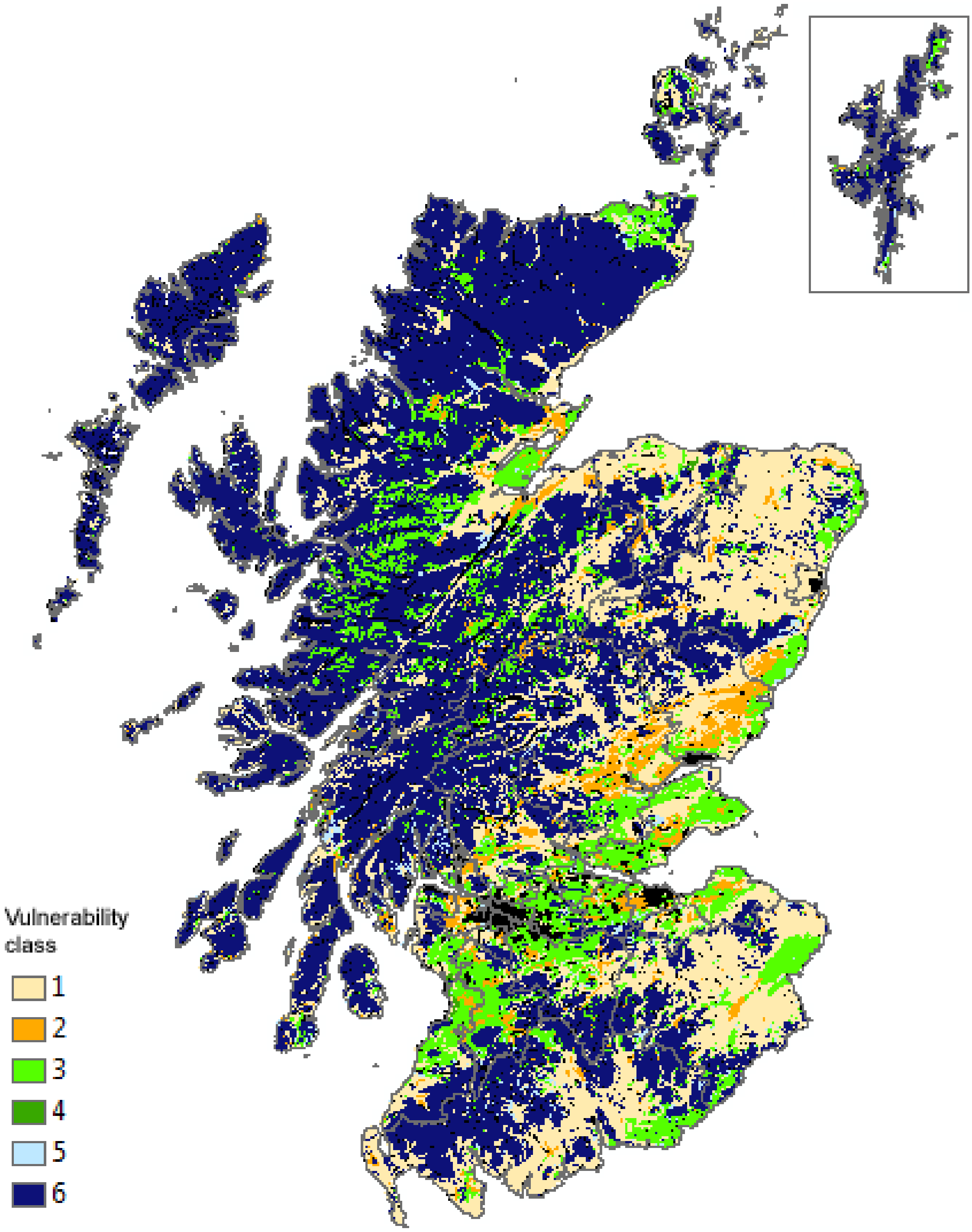


Figure 2

(a)

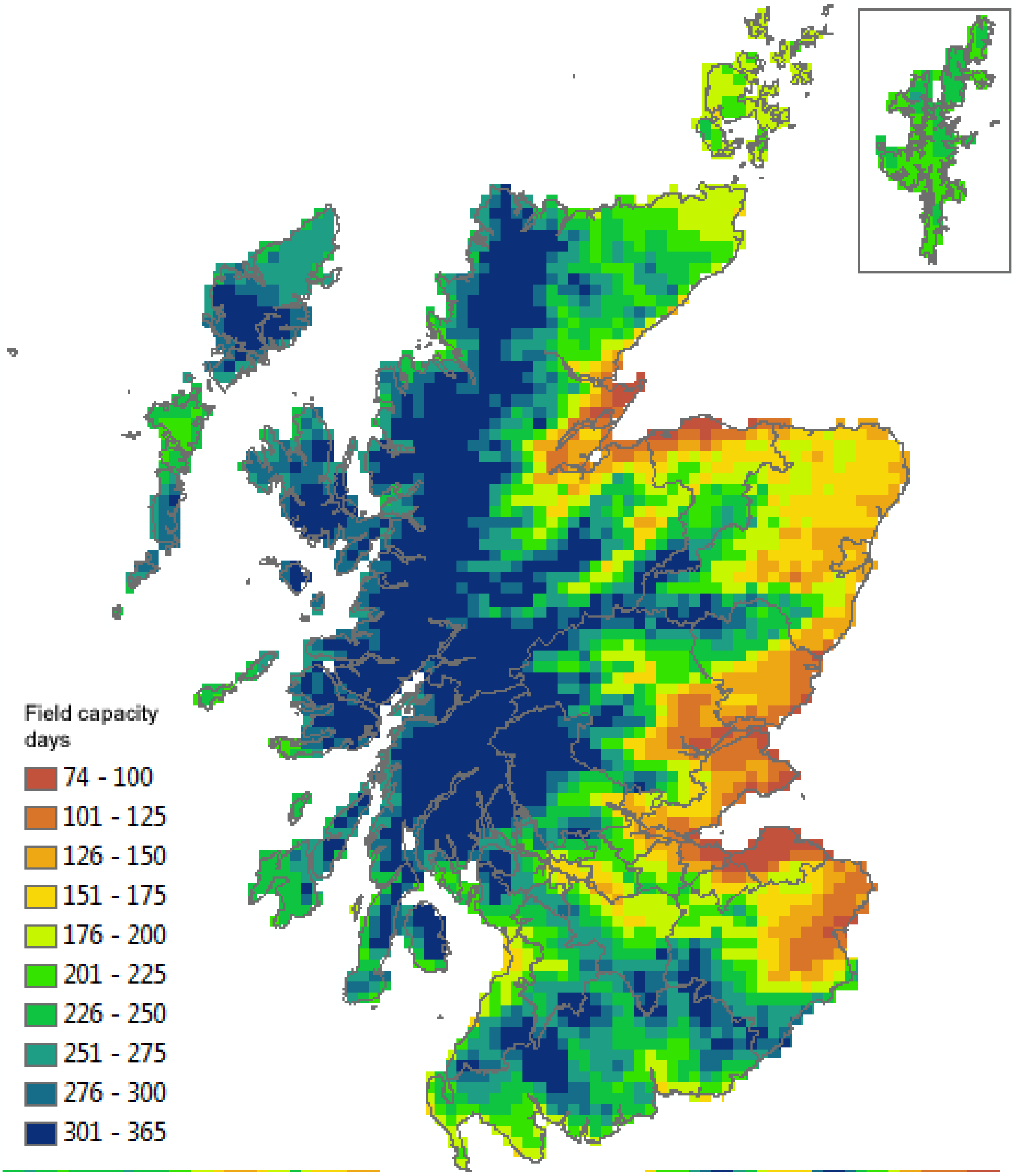

Field capacity days
74 - 100
101 - 125
126 - 150
151 - 175
176 - 200
201 - 225
226 - 250
251 - 275
276 - 300
301 - 365

Figure 3a

(b)

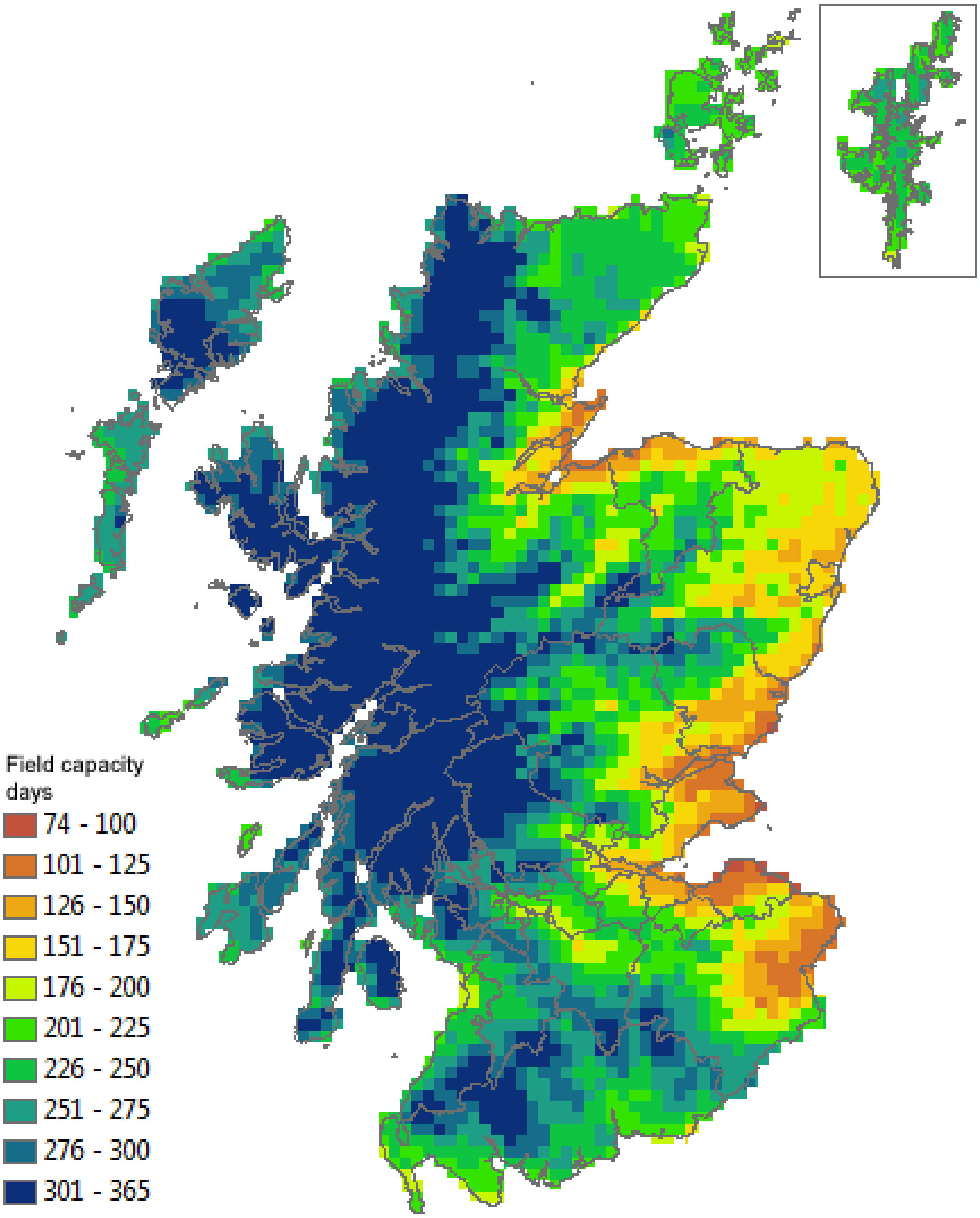

Field capacity days
74 - 100
101 - 125
126 - 150
151 - 175
176 - 200
201 - 225
226 - 250
251 - 275
276 - 300
301 - 365

Figure 3b

(a)

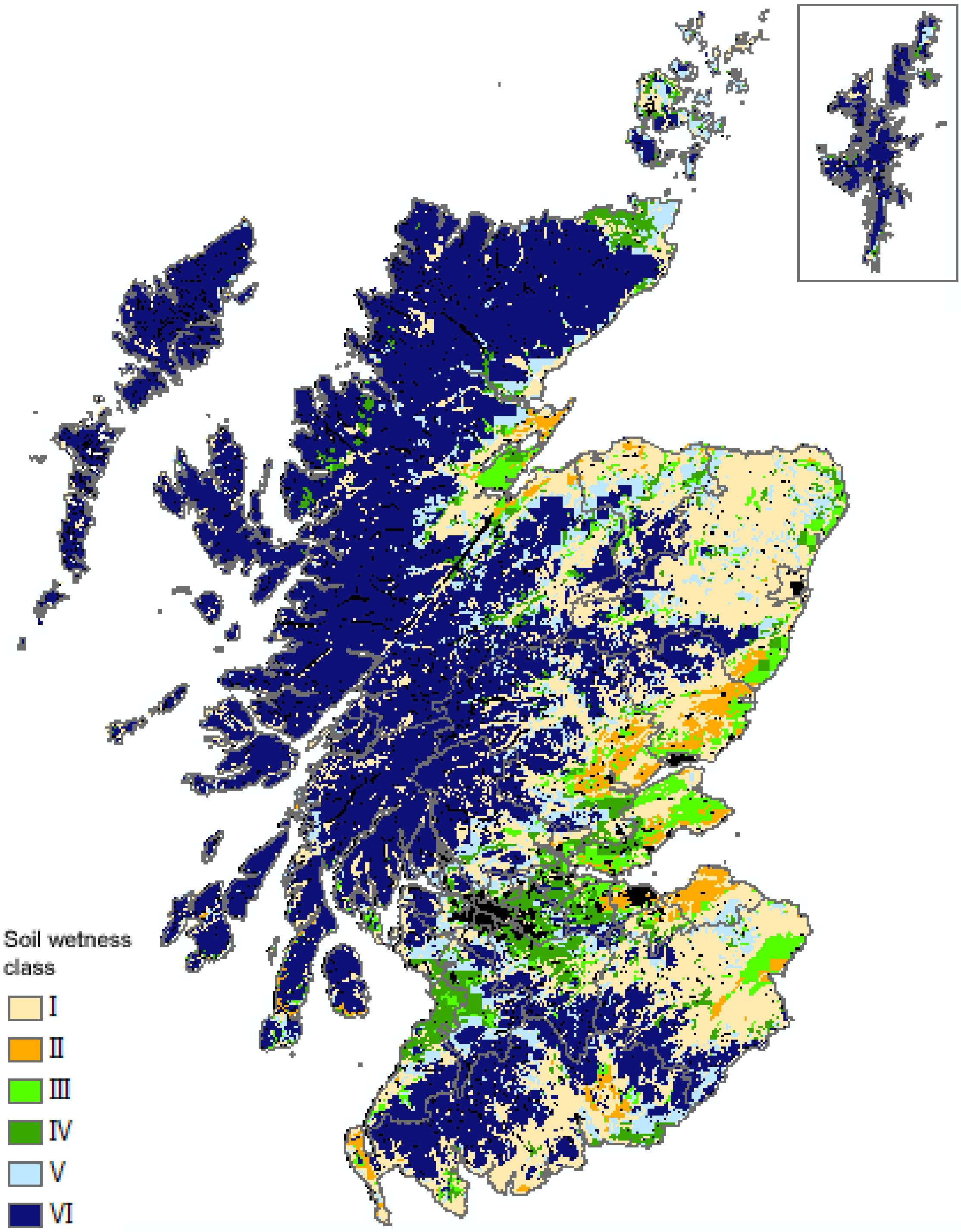


Figure 4a

(b)

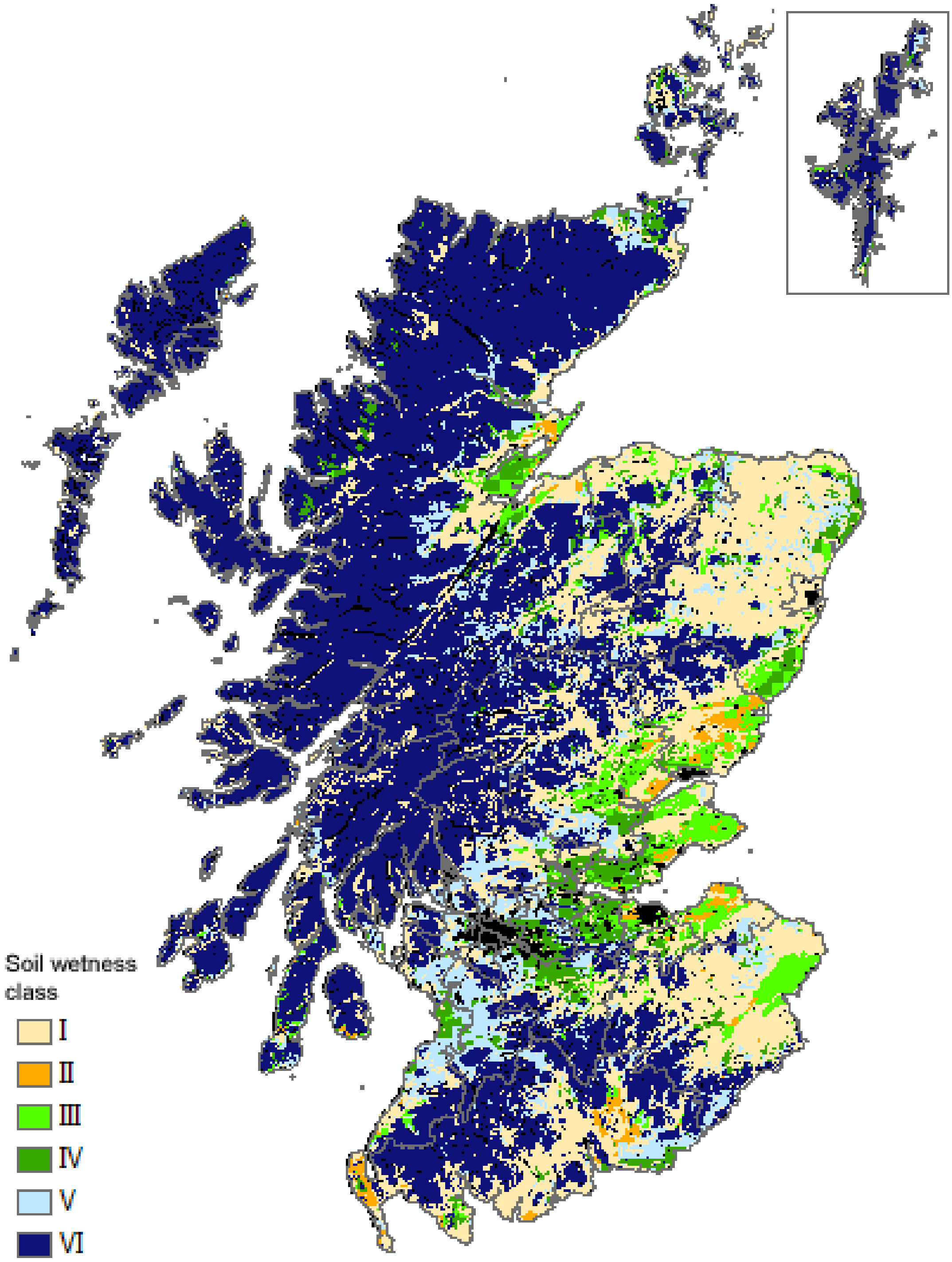


Figure 4b

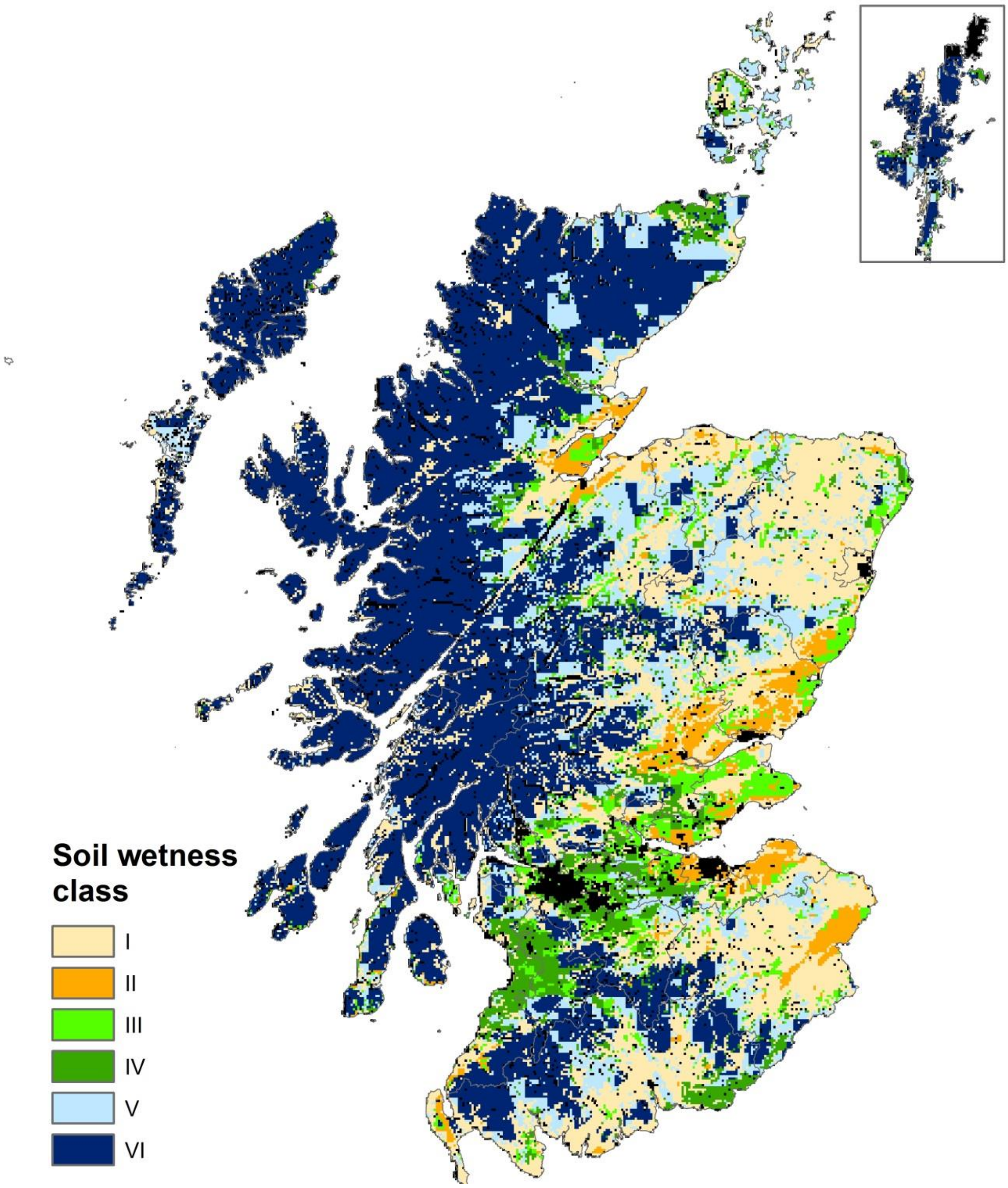


Figure 4c

(a)

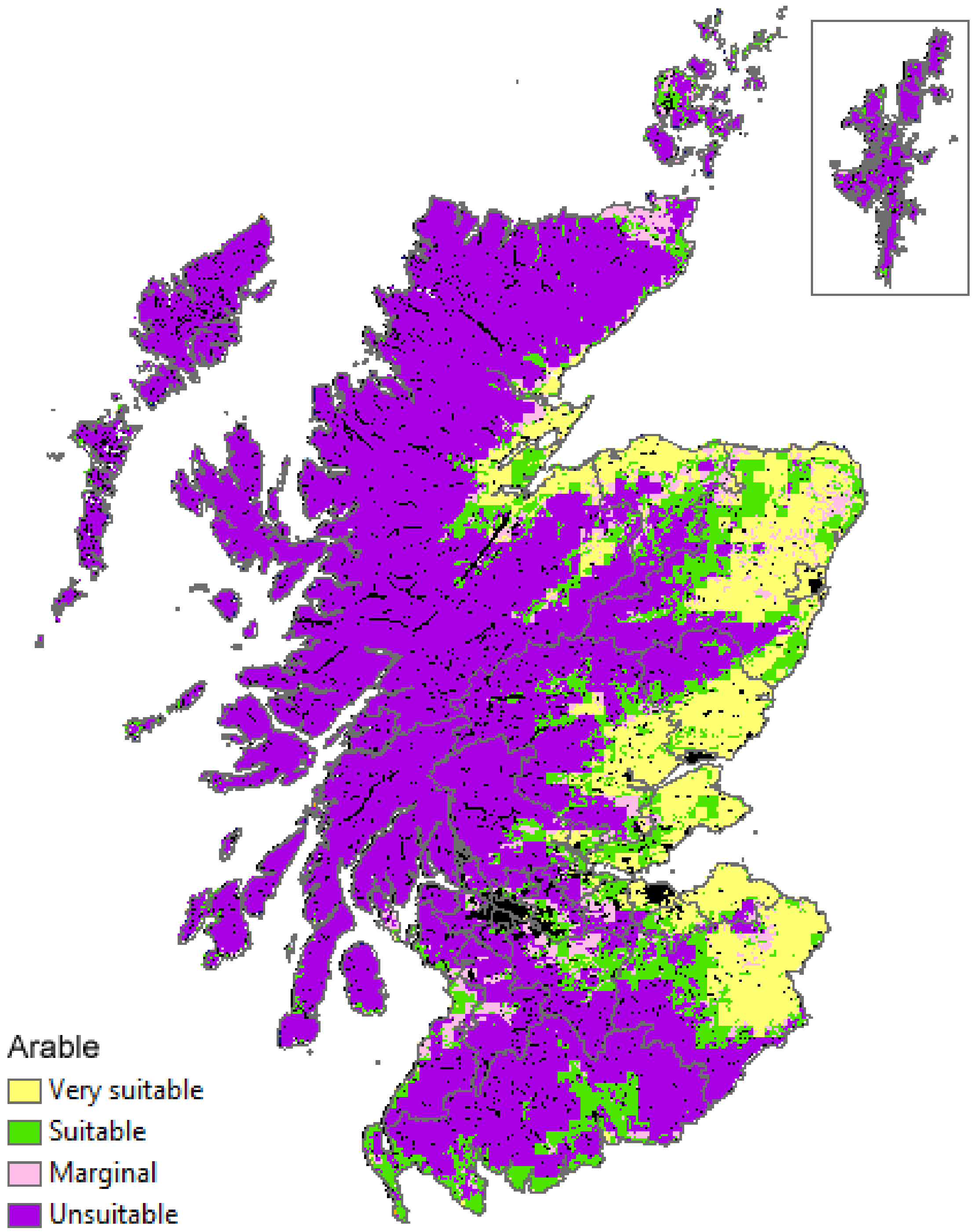


Figure 5a

(b)

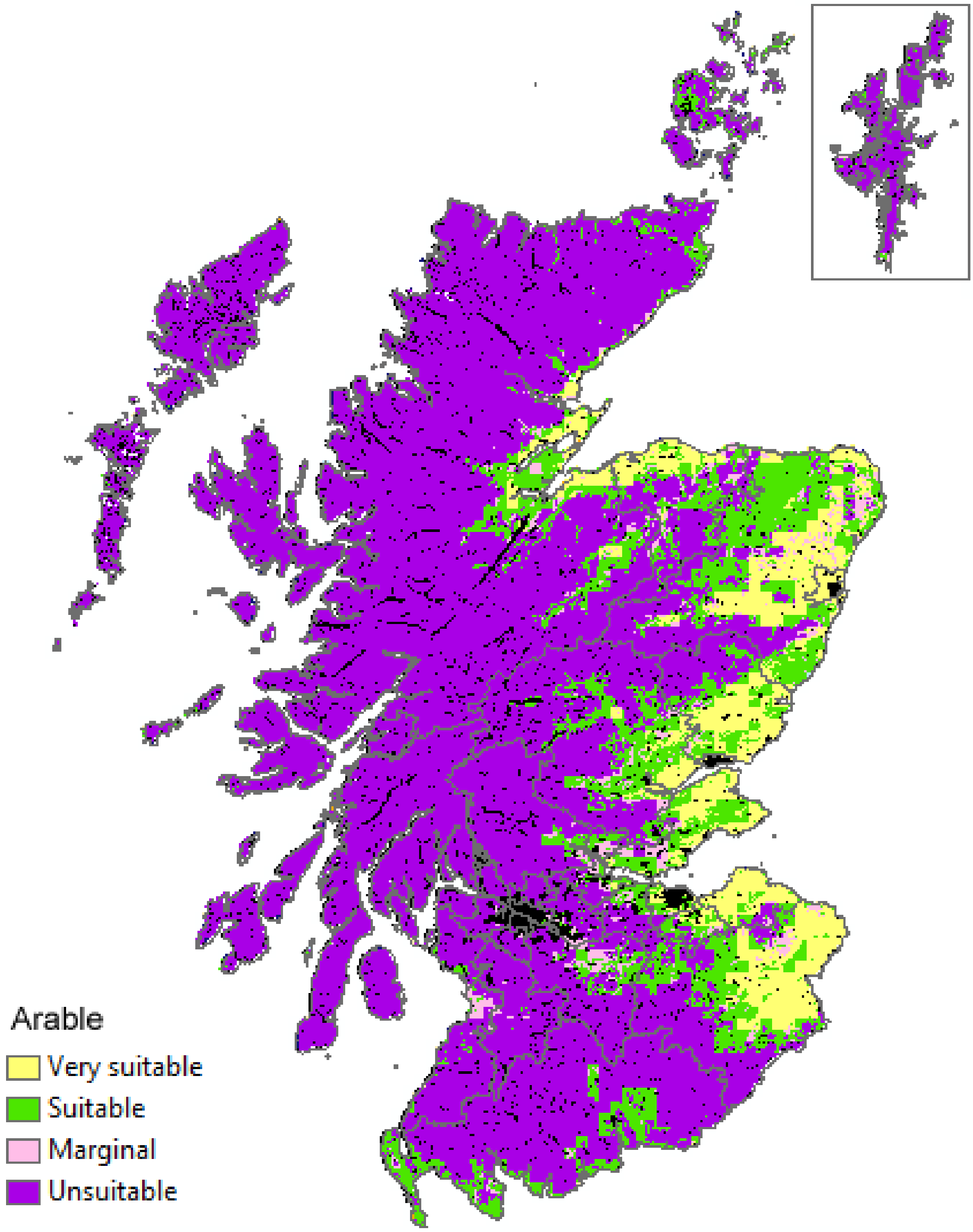


Figure 5b

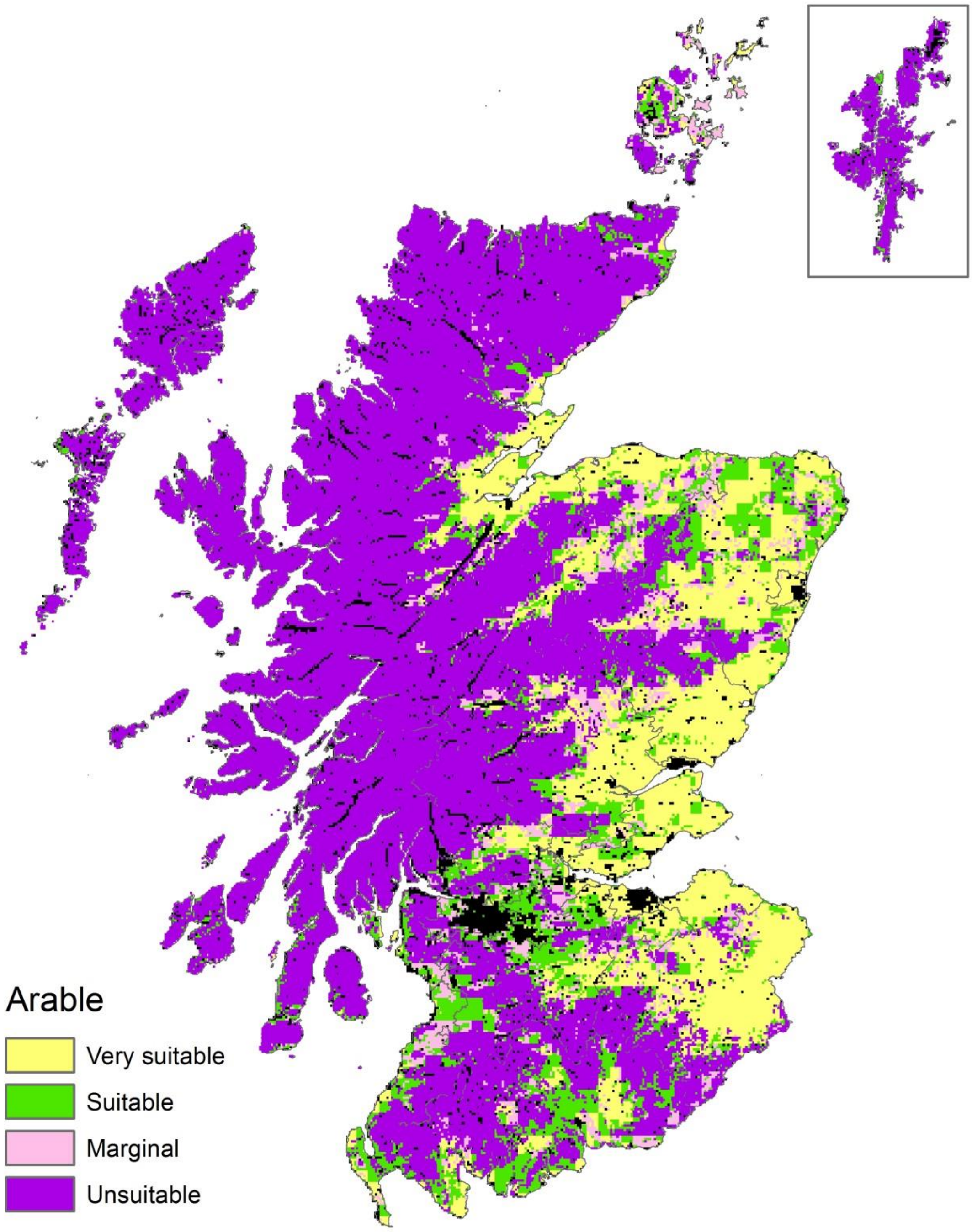


Figure 5c

(a)

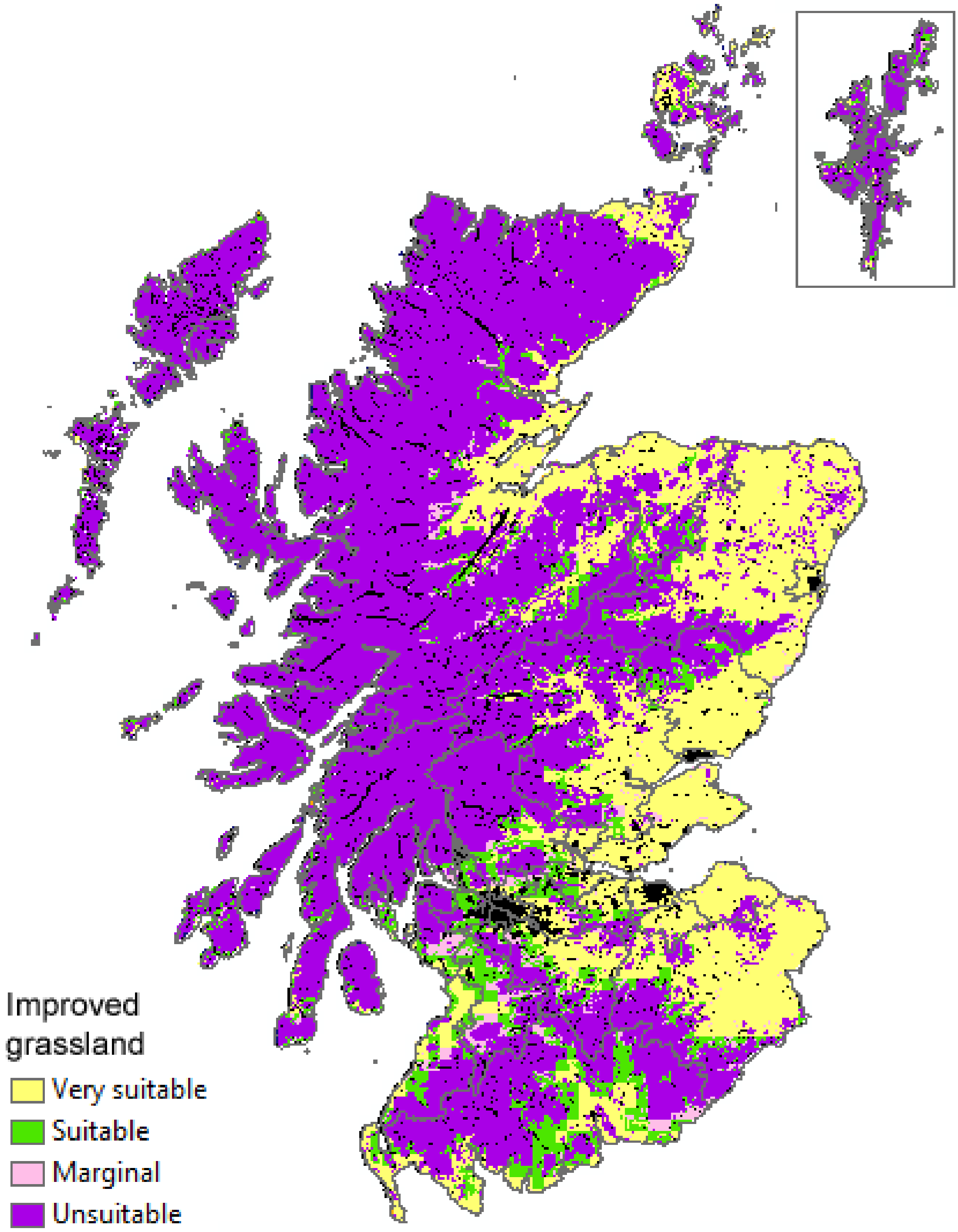

Improved grassland
Very suitable
Suitable
Marginal
Unsuitable

Figure 6a

(b)

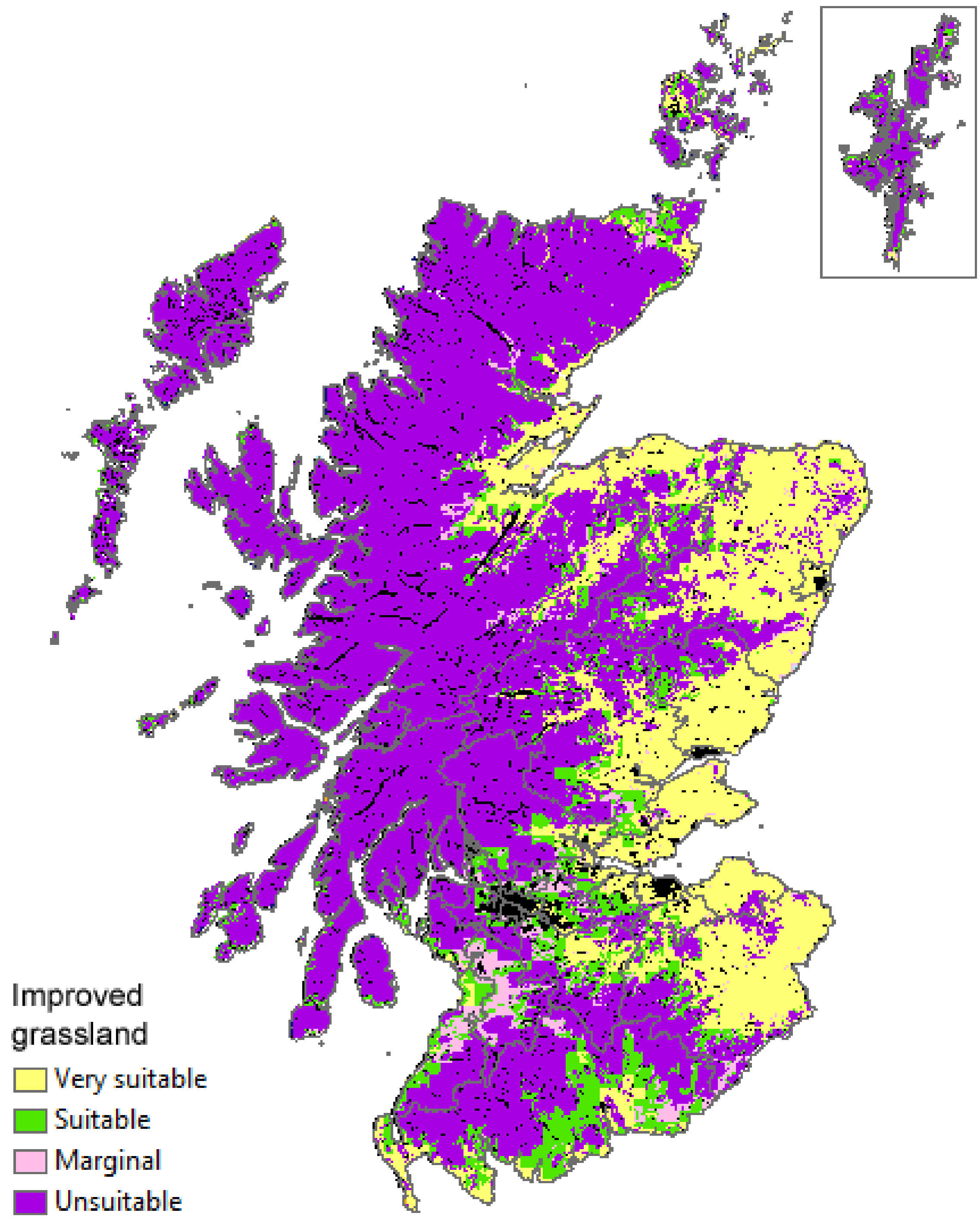
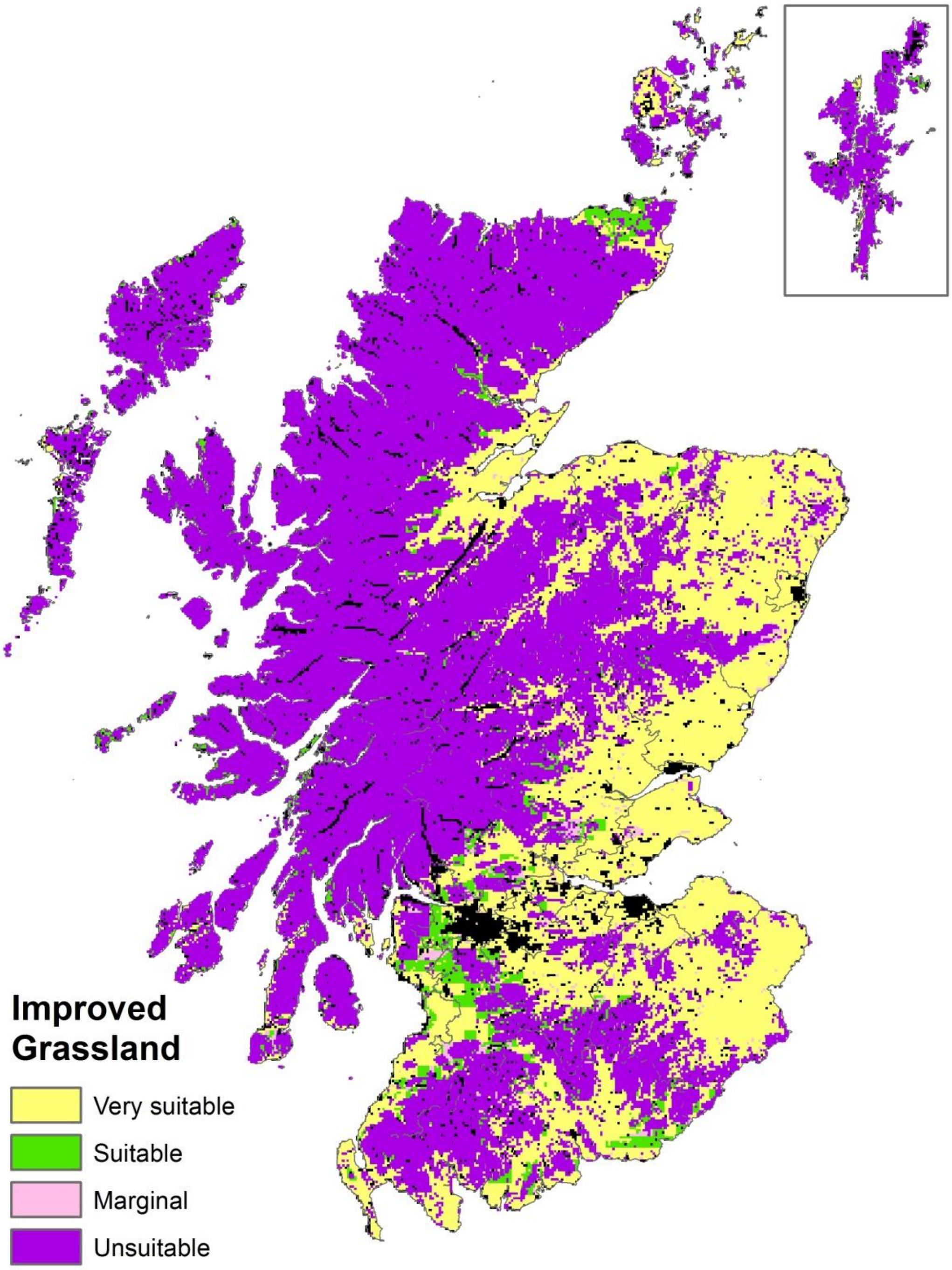

Improved grassland
Very suitable
Suitable
Marginal
Unsuitable

Figure 6b



Improved Grassland
Very suitable
Suitable
Marginal
Unsuitable

Figure 6c

Supplementary Material

Figure S1. Improved agricultural land in Scotland

Figure S2. Soils assumed to have modified properties due to field drainage

Figure S3 Mean days at field capacity in Scotland for the 2050s projection

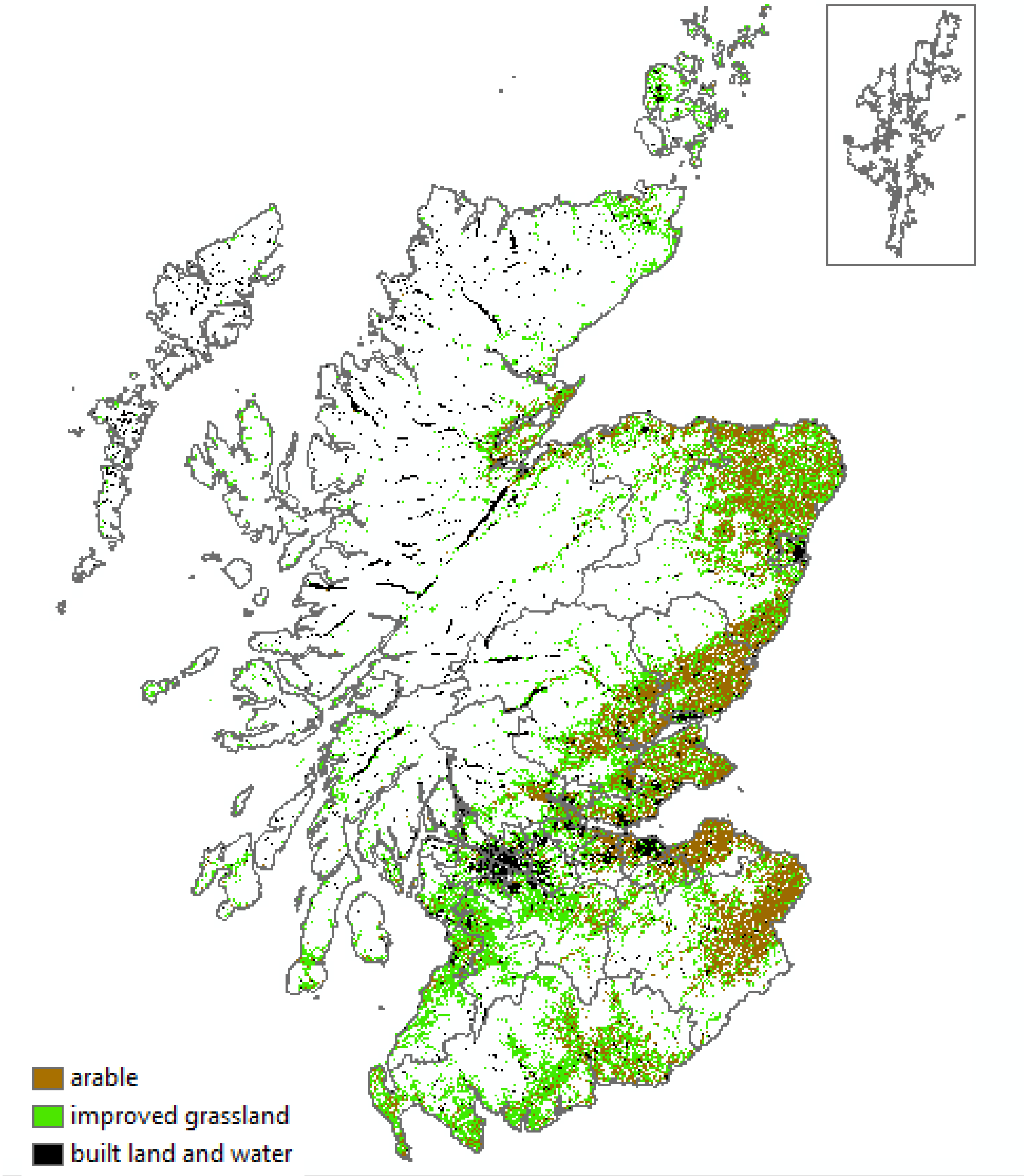


Figure S1

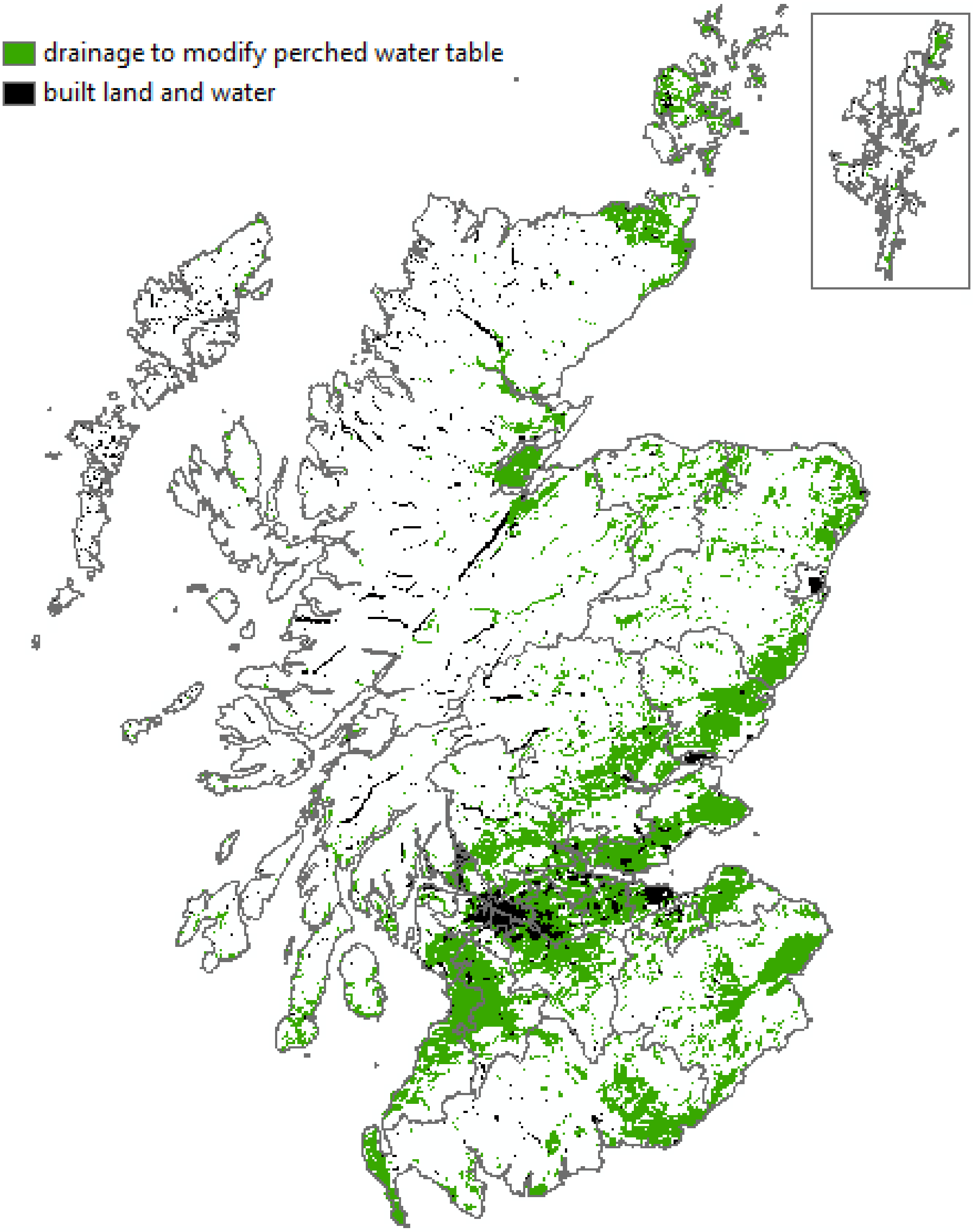

drainage to modify perched water table
built land and water

Figure S2

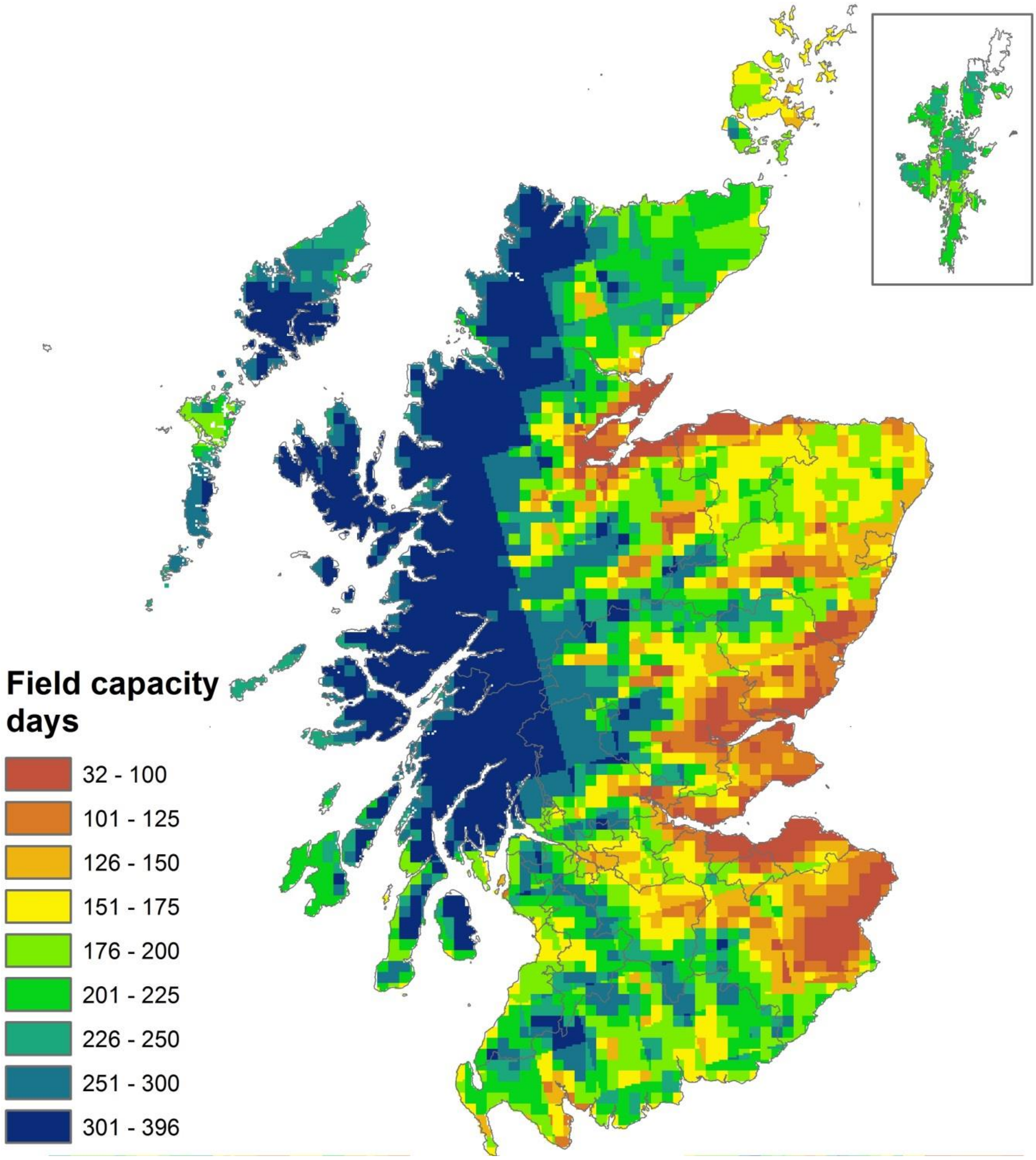

Field capacity days
32 - 100
101 - 125
126 - 150
151 - 175
176 - 200
201 - 225
226 - 250
251 - 300
301 - 396

Figure S3