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ORIGINAL PAPER

Changes in climate variability with reference to land quality and agriculture in Scotland

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Abstract Classification and mapping of land capability represents an established format for summarising spatial information on land quality and land-use potential. By convention, this information incorporates bioclimatic constraints through the use of a long-term average. However, climate change means that land capability classification should also have a dynamic temporal component. Using an analysis based upon Land Capability for Agriculture in Scotland, it is shown that this dynamism not only involves the long-term average but also shorter term spatiotemporal patterns, particularly through changes in interannual variability. Interannual and interdecadal variations occur both in the likelihood of land being in prime condition (top three capability class divisions) and in class volatility from year to year. These changing patterns are most apparent in relation to the west–east climatic gradient which is mainly a function of precipitation regime and soil moisture. Analysis is also extended into the future using climate results for the 2050s from a weather generator which show a complex interaction between climate interannual variability and different soil types for land quality. In some locations, variability of land capability is more likely to decrease because the variable climatic constraints are relaxed and the dominant constraint becomes intrinsic soil properties. Elsewhere, climatic constraints will continue to be influential. Changing climate variability has important implications for land-use planning and agricultural management because it modifies local risk profiles in combination with the current trend towards agricultural intensification and specialisation.

Keywords Interannual variability · Land capability · Land quality · Agriculture · Climate change

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Introduction

Land provides a basic natural resource that supports multiple functions and can deliver a wide variety of services to people. Increasing demands are typically being made upon land resources emphasising the importance of improved knowledge and of knowledge exchange on its efficient and sustainable use. Quality of the land resource is strongly influenced by biophysical factors that define constraints and opportunities, which then interact with socio-economic influences and priorities to determine actual land-use patterns. Land evaluation provides an internationally recognised approach for the characterisation of land quality, including its potential for different uses (FAO 2007). Sustainable land management objectives then aim to reconcile the complementary, yet historically conflicting, goals of production and environment to maintain functioning and productive ecosystems that can provide essential goods and services, particularly food (World Bank 2006).

A key component of land evaluation is provided by land classification systems that provide a rational basis for land-use planning and utilisation of land resources (Davidson 1992). These are usually defined by a combination of intrinsic biophysical factors (e.g. climate, soils and topography) that together summarise constraints and opportunities for land use. The potential for different land uses can then be compared with actual land-use patterns and policy priorities (e.g. food security) in order to strategically plan for a sustainable balance of supply and demand (Brown and Castellazzi 2014).

Classification of land quality is usually made using either parametric systems, based upon numeric correlations between land attributes and yields, or categorical systems which group land into classes with a different land-use potential (van Diepen et al. 1991). The most common categorical approach is provided by land capability classification systems (sometimes also referred to as ‘land suitability’) that originated with the pioneering work of the US Department of Agriculture (Klingebiel and Montgomery 1961) and have now been developed and further refined for many countries and regions (Verheye 2002). Categorical classification aims to summarise the relationship between biophysical constraints and land-use options, usually with a specific emphasis on agriculture, based upon those limitations that cannot be removed or ameliorated by reasonable management. Higher grade land has greater flexibility in potential use, as land of a particular capability class also has the potential to be used as specified for lower classes. When classification is associated with national/regional mapping programmes, identification of both land quality and overall capacity for different uses can be made available to planners to enable strategic resource management.

Bioclimatic constraints on land capability occur due to restrictions on eco-physiological processes such as plant growth rate or by their interaction with different soil types in limiting management activities, especially those related to the timing of specific practises, such as ploughing, sowing and harvesting, or for livestock pasturage (Schulte et al. 2012). A changing climate has major implications for these bioclimatic influences and therefore for land-use planning and sustainable resource use. However, as climate is an integral component of land capability classification and mapping, then by developing dynamic information systems, it should be possible to provide regular updates that can be used to inform policymakers, planners and managers on key aspects of change and hence facilitate appropriate adaptation strategies. This has been exemplified by recent work in the UK that has shown not only changes in land capability classes over recent decades (Keay et al. 2014) but also their extension into the future based upon climate change scenarios (Brown et al. 2008, 2011). As the climate change information is presented to end users in a familiar format (land capability classes), it can provide an accessible medium for knowledge exchange and dialogue on the resultant implications for land-use management and longer term planning.

Previous work on changing land capability has been based upon shifts in long-term multi-year averages that are a feature of established classification systems. However, shorter term variability also has a very important role in influencing the relative viability of different land-use systems (Hudson and Birnie 2000). In particular, interannual variability (IAV) is important for agriculture because of the key role of the annual cycle in both planning and management for crop or livestock systems (e.g. Reilly 2002). A reliably stable and predictable annual cycle means that activities can be scheduled with some certainty, which is particularly crucial in intensive management systems that aim to optimise actions to provide high productivity and higher value produce. By contrast, greater variations in annual conditions mean that it is more difficult to plan in advance, and therefore, some agricultural systems, especially the more intensive ones with specialised crop varieties and management practises, are potentially more vulnerable to these uncertainties (Lin et al. 2008; Lin 2011). Several studies have shown that variations in specific seasonal weather and climate variables can have a strong influence on the yield productivity of crops (e.g. Cantelaube et al. 2004; Atkinson et al. 2005; Iglesias and Quiroga 2007; Marta et al. 2011). It has also been suggested that in some locations, sensitivity of yields to climatic conditions may be increasing, perhaps due to the crop varieties chosen or specialised management practises adopted (Brown 2013).

Improved seasonal weather forecasting provides a potential scope for enhancing preparedness in the agricultural sector (Meinke and Stone 2004). However, serious challenges to reliable seasonal forecasting remain (Doblas-Reyes et al. 2013), particularly for some global macro-regions (e.g. NW Europe), and there are still basic barriers to uptake of this information by farming communities (Matthews et al. 2008). The use of familiar metrics and classification systems, as encapsulated by land capability, can therefore provide an accessible medium to enhance exchange of information on seasonal weather and climatic variability. This is particularly relevant if patterns of IAV are changing, possibly in association with longer term shifts in climate systems due to anthropogenic climate warming, which implies that past patterns of variability may no longer be a guide to the future. Most notably, there is the prospect that patterns of IAV may become more volatile and that both spatial and temporal patterns may be modified (Graux et al. 2013).

Shorter term variability influences land capability classifications because, although the established classification is based upon a long-term average, the results are sensitive to the time period used to define the long-term average (Hudson and Birnie 2000; Brown et al. 2008). However, land that is significantly more variable from year to year should intuitively have a lower class rating compared to equivalent land with the same average land capability but a more stable annual class. High variability may effectively constrain some land-use options due to the higher risks involved, meaning the land is less flexible in its uses. Currently, established classification systems do not incorporate this variability, despite its increasing relevance for adaptive resource management in a changing climate.

Data and methods

Scotland provides a suitable case study to investigate this topic because of its inherent climatic variability and because the perceptions of farmers in some regions are that patterns of variability are changing (Barnes and Toma 2012). Land quality in Scotland has large variations, from areas which are very versatile and can produce very high crop yields in contrast to other areas which are either very limited or incapable of supporting any type of agricultural activity due to intrinsic constraints. The analysis is based upon the national Land Capability for Agriculture (LCA) classification (Bibby et al. 1982; Table 1) which is widely utilised by planners and managers. An important aspect of LCA is the definition of the best quality land, defined as 'prime agricultural land', based upon its top three units, because this land has a protected status in the planning system. LCA integrates climate data with soil properties and topography to define viable land-use options based upon extensive field experience which acts to support its continuing utility.

The climatic component of LCA is primarily based upon two bioclimatic metrics, accumulated temperature and maximum potential soil moisture deficit, that are combined in a two-dimensional array to define unit classes with boundaries based upon empirical evidence of land-use patterns: Two of the classes have further climatic sub-divisions: $3_1/3_2$ and $4_1/4_2$ (Fig. 1; Bibby et al. 1982). These two metrics have important relationships to agricultural productivity and sustainable land-use practices. Accumulated temperature provides a measure of the influence of the length and intensity of the growing season which is particularly important for grassland productivity in marginal areas (Solhaug 1991) where livestock rearing is important. Soil moisture deficits are important for a range of agricultural activities and crop productivity, with previous research in Scotland showing that they are a very good indicator of annual yields in high-value crops such as potatoes and cereals (Brown 2013). When combined together, these two metrics can define the range of LCA classes. The analysis is based upon the spatiotemporal variation of these classes at annual time steps and for the summary classification through long-term averages; by convention, a 20-year period is used for averages in the LCA system. Data for the analysis were sourced from both observations (recent changes) and climate models (future changes).

Observed climate data

Climate observations were obtained from a 5-km gridded monthly climatology produced by the UK Met Office (UKMO) for 1961–2011 using a standardised methodology (Perry and Hollis 2005). This climatology was produced from quality-checked station data using a multiple regression method incorporating geography and elevation with coastal and urban effects, followed by distance-weighted spatial interpolation onto a 5-km grid. Station density for the interpolation was reported as 150–200 per 100 km^2 for rainfall data and 15–30 per 100 km^2 for other meteorological data.

Climate model data

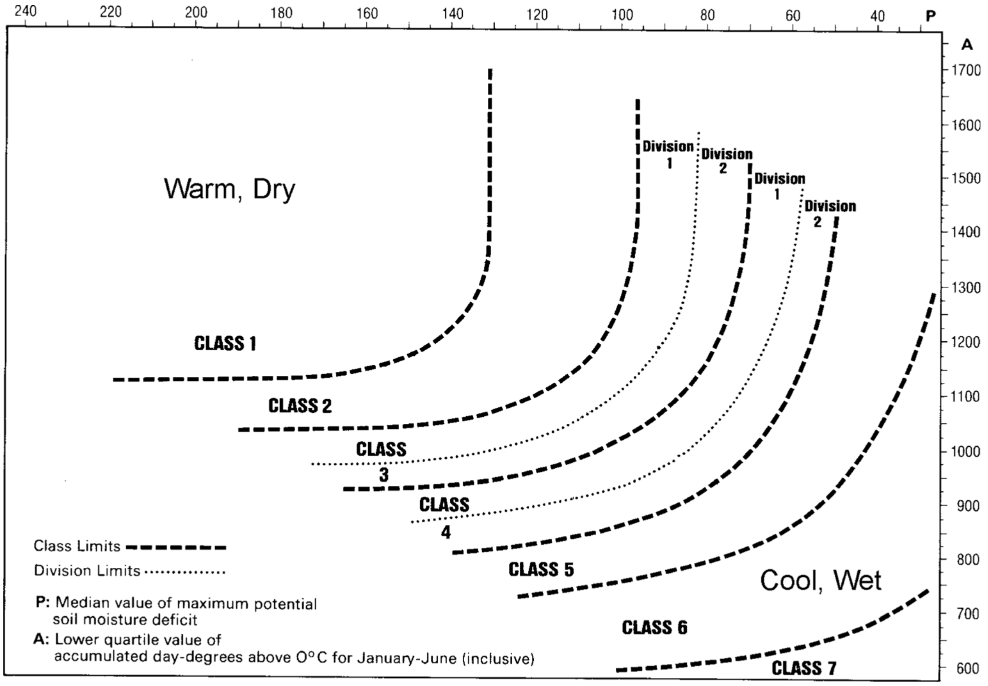
Despite recent advances in nested regional climate models, it is not yet possible to obtain high-resolution climate change data that can robustly discriminate local climatic differences due to topography and other geographic factors. As a consequence, further downscaling is required of climate model data. To explore future changes in IAV, the study used a weather generator (WG) developed for the UK Climate Projections 2009 (UKCP09) (Jones et al. 2009) to derive present and future data for selected sites in Scotland. The generated data are based upon statistical relationships derived from the same aforementioned UKMO 5-km observed climatology (Perry and Hollis 2005) that are then perturbed based upon climate change using a stochastic routine to generate multiple simulations. The WG allows the climate change factors derived from the UKCP09 multi-model climate ensemble to be applied to the selected locations to derive future climates (2041–2070) by comparison to the control baseline period (1961–1990); this is achieved by each simulation representing a sample from the 10,000 model variants that make up the UKCP09 probabilistic projections.

The WG was run at seven selected locations based upon three pairs of closely adjacent sites in south-west, south-east

Table 1 The LCA classification for Scotland

Class	Category	Climate limitations	Land-use potential
Class 1	Prime	None or very minor	Very wide range of crops with high yields
Class 2	Prime	Minor	Wide range of crops with high yields
Class 3_1	Prime	Moderate	Moderate range of crops, with good yields for some
Class 3_2	Non-prime	Moderate	Moderate range of crops, with good yields for barley, oats and grass
Class 4_1	Non-prime	Moderately severe	Narrow range of crops, especially grass due to high yields. Very suitable for improved grassland
Class 4_2	Non-prime	Moderately severe	Primarily improved grassland due to high yields but with some fodder crops possible
Class 5	Non-prime	Severe	Improved grassland, with mechanical intervention possible
Class 6	Non-prime	very severe	Rough grazing pasture only
Class 7	Non-prime	Extremely Severe	Very limited agricultural value

Fig. 1 The two-parameter bioclimatic classification used for LCA



and north-east Scotland that have the same climate but different soils; a further site was chosen in northern Scotland, but this was not paired because there are no soil types here in the highest LCA classes. The range of sites allowed spatial variations in climate and soils to be compared against dynamic temporal changes in climate as intrinsic soil properties were assumed to remain constant. At each chosen site, 100 WG simulations of baseline and future climate were generated. A single greenhouse emission profile was used (IPCC A1B: Nakicenovic et al. 2000) as it was assumed that variations in GHG emissions would have a much lesser influence on the climate response for the 2050s compared to parameter uncertainty across climate models (i.e. climate sensitivity) due to the long lag time involved with emission-generated radiative forcing.

Calculation of bioclimate metrics

Accumulated temperature (AT0) This is an indicator of the amount of energy available for crop growth and is produced by summing mean daily temperature values above the threshold value of 0 ° C to provide a monthly aggregate in degree-days. Using a value of 0 ° C, rather than 5.6 ° C which is often used for a growing degree-days threshold, is justified because of the small but significant leaf growth in both cereals and grass occurring at lower temperatures down to 0 °C (Brown et al. 2008). The metric is restricted to the first 6 months of the year (January–June inclusive) as this is the most important period for grass and other crop yields and to exclude the potentially detrimental effects of higher temperatures in the latter half of the year. By convention, in the LCA system, long-term averages are calculated using the lower quartile AT0 value from the 20-year reference time period.

Maximum potential soil moisture deficit (MPSMD) Soil moisture deficit provides the balance between precipitation and evaporation over a year. Typically, soils become drier for a period of time due to the excess of evaporation over precipitation and therefore reach a notional maximum deficit. Evaporative losses are estimated using the FAO56 version of the Penman–Monteith potential evapotranspiration (ET_0) equation for a reference surface of grass (Allen et al. 1994), therefore assuming an unlimited supply of water from the soil. The UKCP09 WG provides data in the same FAO56 format for ET_0 (Jones et al. 2009). The soil moisture deficit is calculated through the year using a running accumulator of the net balance of ET_0 against precipitation when it is reduced below 0 mm (field capacity) (Brown et al. 2008). This provides a reference value of potential deficit rather than the actual deficit which would require more detailed local information on soil properties (including the presence of field drains) and adjustment for different land cover (vegetation) types. MPSMD therefore provides the maximum potential deficit during a year and provides a good indicator of the amount of time when the land is unsaturated and therefore likely to be in a workable condition; it can therefore provide a key climatic measure of potential crop yields and land-use flexibility (Baier and Robertson 1968; Brown 2013). The long-term average is summarised through the median value for 20 years.

Calculation of LCA classes

The final LCA class is defined by integration of the bioclimate metrics (yearly values or long-term average), with soil and topographic constraints. As the LCA is an empirical classification, class boundaries were originally defined and validated based upon field evidence. Soil constraints are based upon key criteria that influence agricultural suitability, notably depth, structure, texture, organic matter and stoniness, which also influence soil–climate interactions such as wetness and drought risk. These criteria were used to assign each map unit used in the 1:250,000 soil mapping for Scotland to an LCA class based upon the classification of each unique soil series (Brown et al. 2008). This mapping shows that a large proportion of Scotland is underlain by soils that have intrinsic constraints meaning they cannot be defined as prime agricultural land (Fig. 2), regardless of other factors. Topographic slope data were derived from a 25-m Ordnance Survey digital elevation model. However, when climate, soil and topographic data were aggregated together on a 1-km grid, the topographic data became subordinate to the other two data sources, with soil data providing the local variation at the level below the 5-km resolution of the climate data. The 1:250,000 scale soil mapping can have limitations at local level due to generalisation of unit boundaries (minimum size of map unit ca 75 ha); this may be refined by higher resolution mapping, but as this was only available for selected areas, it was not incorporated here. During data aggregation, the final LCA class was based on the most limiting factor, either due to the dominant restriction being climate-based or soil-based at this 1-km scale (Fig. 3).

Spatiotemporal analysis

The LCA classification of Scotland was performed for the years 1961 to 2011, which also allowed the derivation of longer term 20-year means to be summarised for an assessment of decadal changes in IAV. In addition to the spatial extent of all LCA classes, change data were summarised using three main measures:

(i) The spatial extent of land defined as ‘prime agricultural land’ for each year
(ii) The likelihood of a 1-km gridcell being defined as ‘prime agricultural land’ for a summary 20-year period
(iii) A ‘volatility index’ to summarise IAV of LCA classes for a 1-km gridcell over a 20-year period. This was calculated based upon an accumulated running sum of

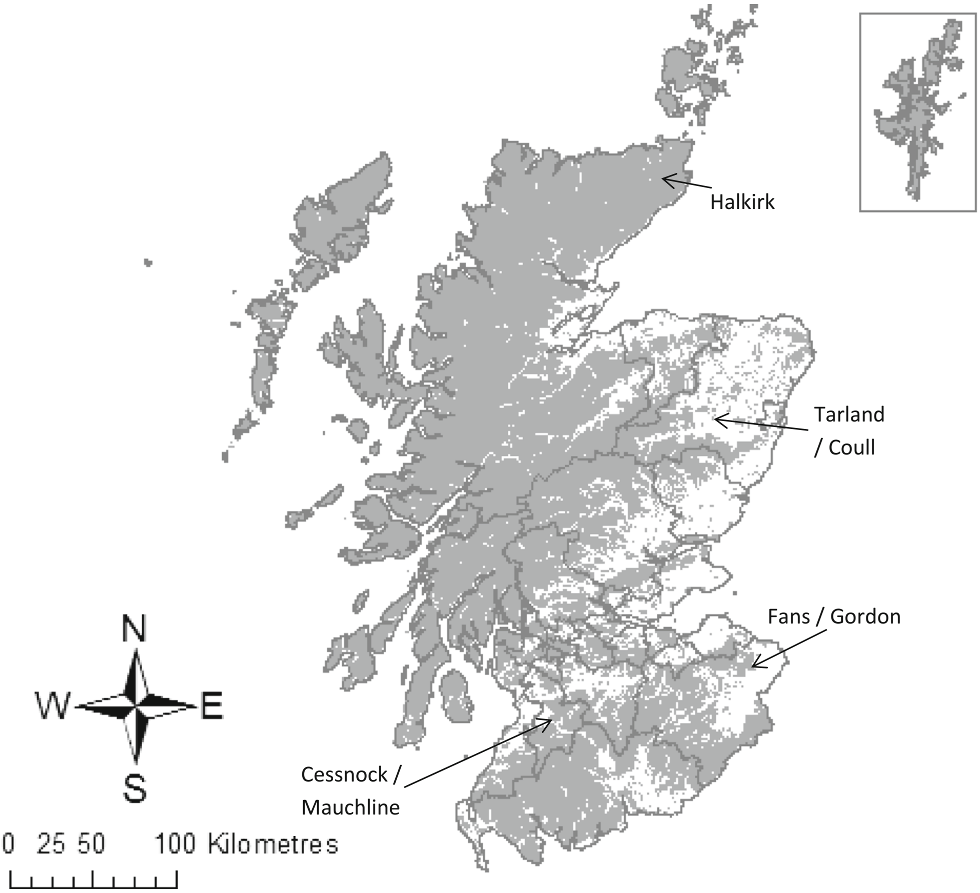
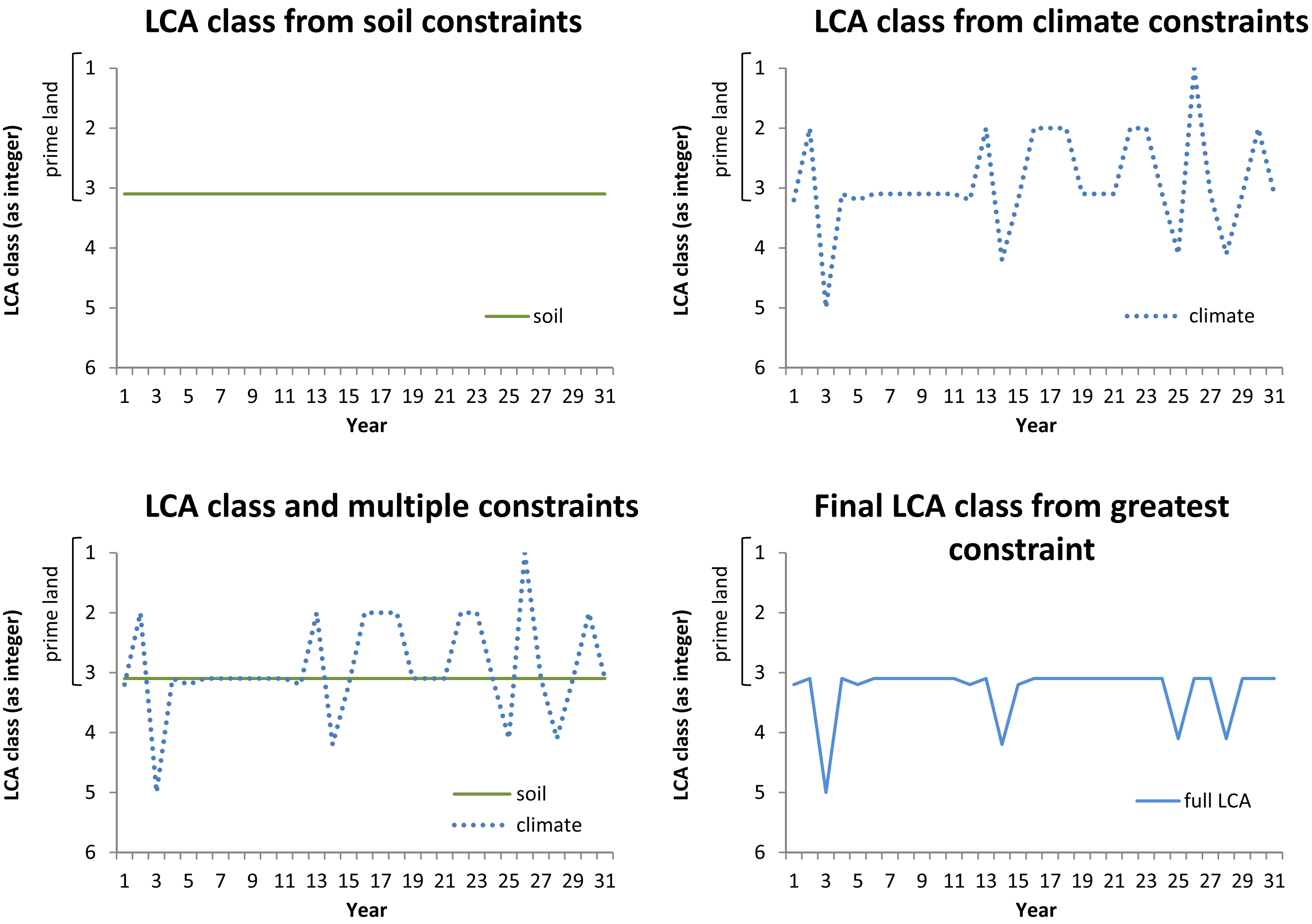


Fig. 2 Soils that are constrained from being prime land due to intrinsic limitations with sites selected for WG runs


LCA class from soil constraints

LCA class from climate constraints

LCA class and multiple constraints

Final LCA class from greatest constraint

Fig. 3 Schematic of final annual LCA class assignment based upon the greatest constraints provided by soil or climate LCA class

the difference in LCA classes for each year compared to the previous year. Hence, if the LCA class for 1961 was class 5 and for 1962 was class 3, then the difference was assigned as 2, followed by a similar calculation for all years to 2011. For the calculation of this index, only the main class was used (e.g. class 3) and not class divisions (e.g. class 3.1).

For the sample locations used in the future projections, only steps (ii) and (iii) were applied. For validation purposes, the results from the weather generator projections could be compared against those from the observation data for the same location and reference period.

Results

Recent changes

The summary LCA classification based upon 20-year means shows that over four overlapping periods the LCA classes are not stationary (Table 2; Fig. 4). This is particularly apparent between the two periods 1961–80 and 1971–90 when there was a large expansion (from 9.8 to 13.9 %) in prime land classes (1–3_1) and also an increase (from 40.8 to 46.3 %) in those classes (1–5) which define land that has potential for agricultural improvement. Between these two periods, the most pronounced changes are the increase in prime agricultural land and improvable land in SW Scotland. Since the 1971–1990 period, the total changes have been much smaller, with a fractional increase in prime land (0.4 %) and virtually no change in potential improved land (−0.02 %) through 1981–2000 to 1991–2010. However, these totals mask important geographic patterns; notably, that prime and improvable land has decreased in south-west Scotland after 1971–1990, but both types of land have increased in eastern Scotland, particularly prime land in north-east Scotland. Nearly all of north-west Scotland has remained unchanged in LCA classes throughout the period of analysis due to the continuing severe climatic constraints.

Shorter term analysis based upon the yearly extent of prime agricultural land shows that considerable IAV of land quality occurs (Fig. 5). Over the full period 1961–2011, there are some years where a considerable proportion of the country may be considered as in 'prime' climatic condition (e.g. 1974,

Table 2 Summary (in %) of the LCA classes over the four reference periods

LCA class	1961–1981	1971–1990	1981–2000	1991–2010
1	0.01	0.06	0.07	0.04
2	3.5	5.6	5.6	5.7
3.1	6.3	8.2	8.6	8.4
3.2	7.5	9.4	7.6	7.8
4.1	5.9	5.5	5.1	5.4
4.2	3.0	2.1	2.5	3.1
5	14.6	15.3	15.0	15.3
6	50.7	45.3	47.2	47.7
7	5.0	5.3	5.0	3.2
Unclassified	3.4	3.4	3.4	3.4

1976, 1989 and 2008), whereas by contrast, there are other years (e.g. 1985, 1987, 1998, 2004) in which virtually no land is defined in ‘prime’ condition. Moreover, it is possible for poor years to follow the good years in close succession, or vice versa (e.g. 1984 and 1985; 1979 and 1980; 2003 and 2004), with no evidence of a regular cycle, which highlights the difficulties for land managers due to the apparent unpredictability of the interannual sequence. During years of relatively good weather, the geographic constraints on land capability become dominated by intrinsic soil properties which define a maximum extent for prime land (Fig. 2) despite the favourable weather. However, during years of poor weather, the climatic constraints become more dominant, and in some years, this means that virtually no land is in prime condition resulting in management difficulties more commonly associated with land in lower classes occurring for all the country.

The likelihood of land being in prime condition over the standard 20-year periods is shown in Fig. 6. Although the broad geographic patterns are similar over these periods indicating that some locations are generally more exposed to IAV than others, there are some important temporal differences between periods. This is particularly exemplified for several areas of eastern Scotland that saw an increased likelihood of land being classed as prime for the periods 1961–1980 to

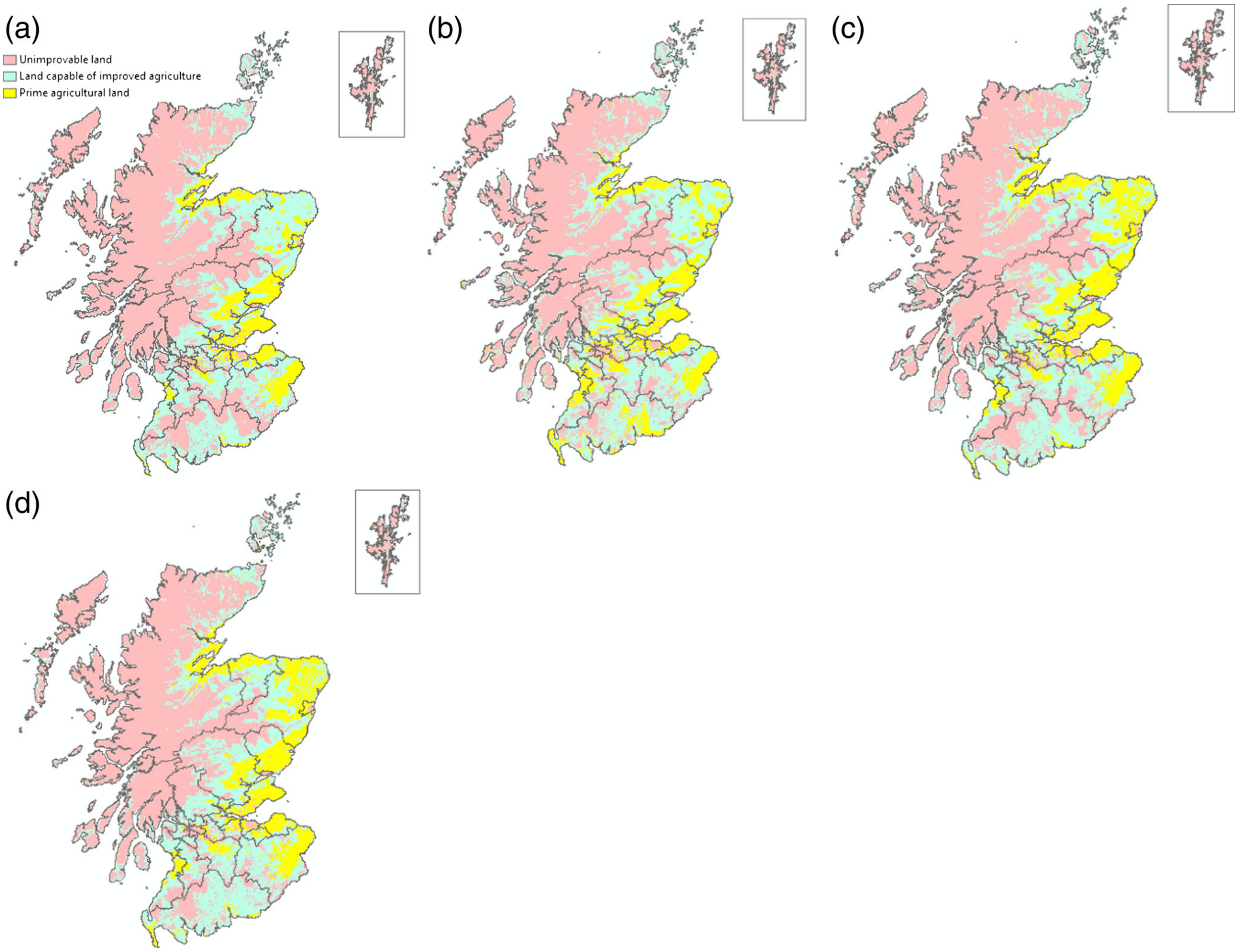


Fig. 4 LCA classification for **a** 1961–1980, **b** 1971–1990, **c** 1981–2000 and **d** 1991–2010

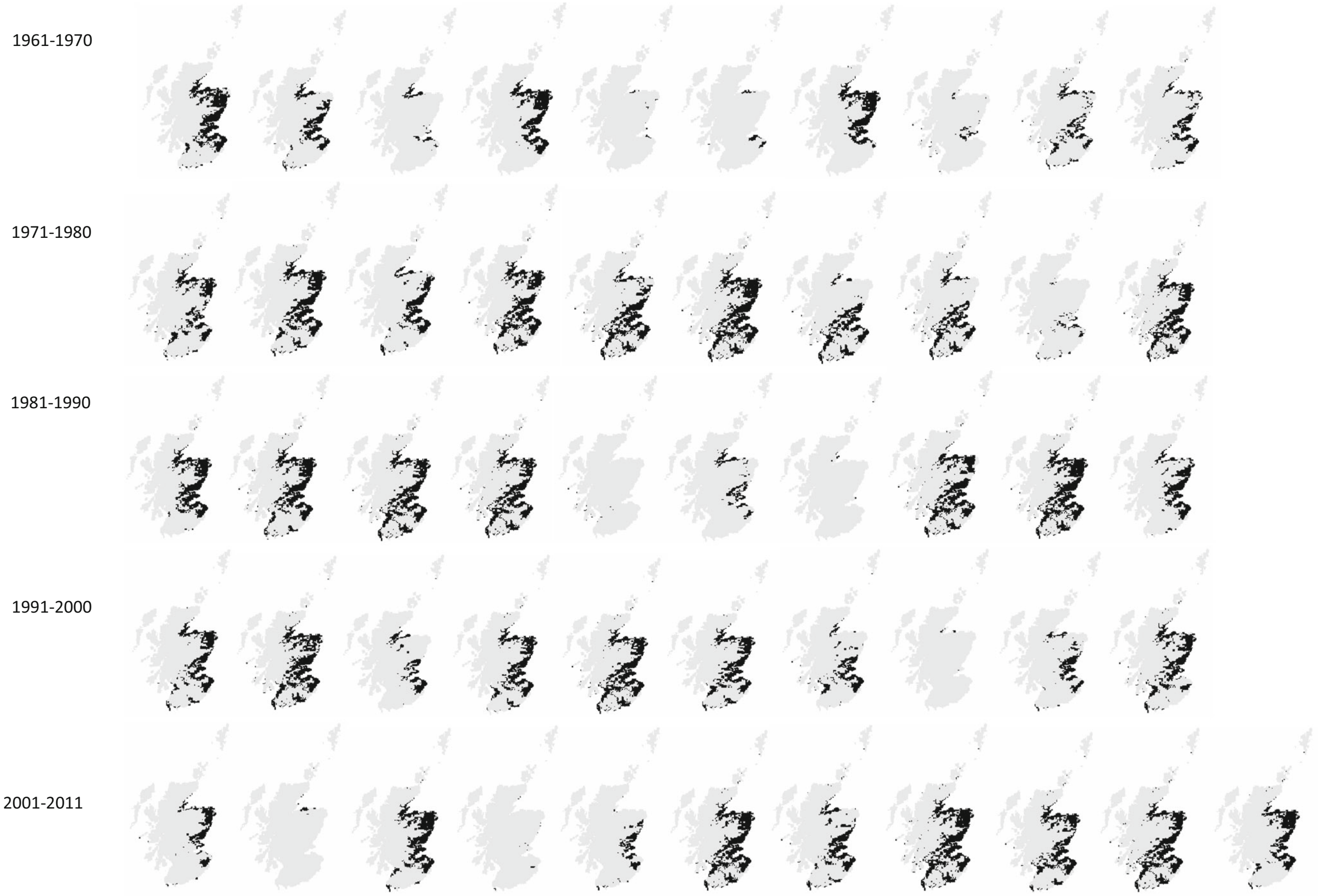


Fig. 5 Area of prime land for the years 1961–2011

1971–1990 and also extending to 1981–2000. However, for the most recent period, 1991–2010, there has been a slightly decreased likelihood of land being classed as prime in these same areas of eastern Scotland due to a small increase in wetter years. A similar decreased likelihood for the most recent period is evident in south-west Scotland. When the likelihood of being prime is summed across all of the years from 1961 to 2011 (Fig. 7), then it is notable that no location in Scotland was in prime condition for all these years, although some localities did have a very high proportion of prime years.

Finally, the aggregated volatility index for the same 20-year reference periods is presented in Fig. 8. This shows that areas of greatest LCA class volatility are the more marginal locations for agriculture in the upland/lowland transition zone where the annual weather patterns have the greatest influence in causing class differences from year to year. These locations are in a transition between favoured lowland locations that generally have a more stable climate, and therefore more likely to meet the climatic threshold for prime land, and upland locations that are unfavourable because of unsuitable soils and severe climate constraints. Areas with a volatility index exceeding 20 typically experience a change of at least one LCA class between successive years, whereas those over 40 can typically experience a change in two classes between years. When looking at change across the 20-year reference periods, it can be inferred that for many areas of eastern Scotland, the volatility has decreased, with a slight reversion to increased volatility in the most recent period (1991–2010). However, by contrast, volatility has apparently increased in south-west Scotland throughout successive periods from 1961–1981 to 1991–2010.

Future changes

The WG data for the selected locations are summarised in Table 3 with comparison against the observed data for the 1961–80 period calculated using the same volatility index. This comparison shows that the observed value lies within the range of simulated values but that it is towards the maximum simulated value of these runs; hence, the median of the simulated values is usually much lower, highlighting that the WG tends to underestimate the variability. For two of the sites (Fans and Gordon), 1,000 WG simulations had to be generated to achieve an acceptable range that would cover the observed value because for 100 simulations, the range was too narrow. These sites in south-east Scotland have lower climatic IAV than the others, and this seems to have been further smoothed by the WG procedure. The general underestimation

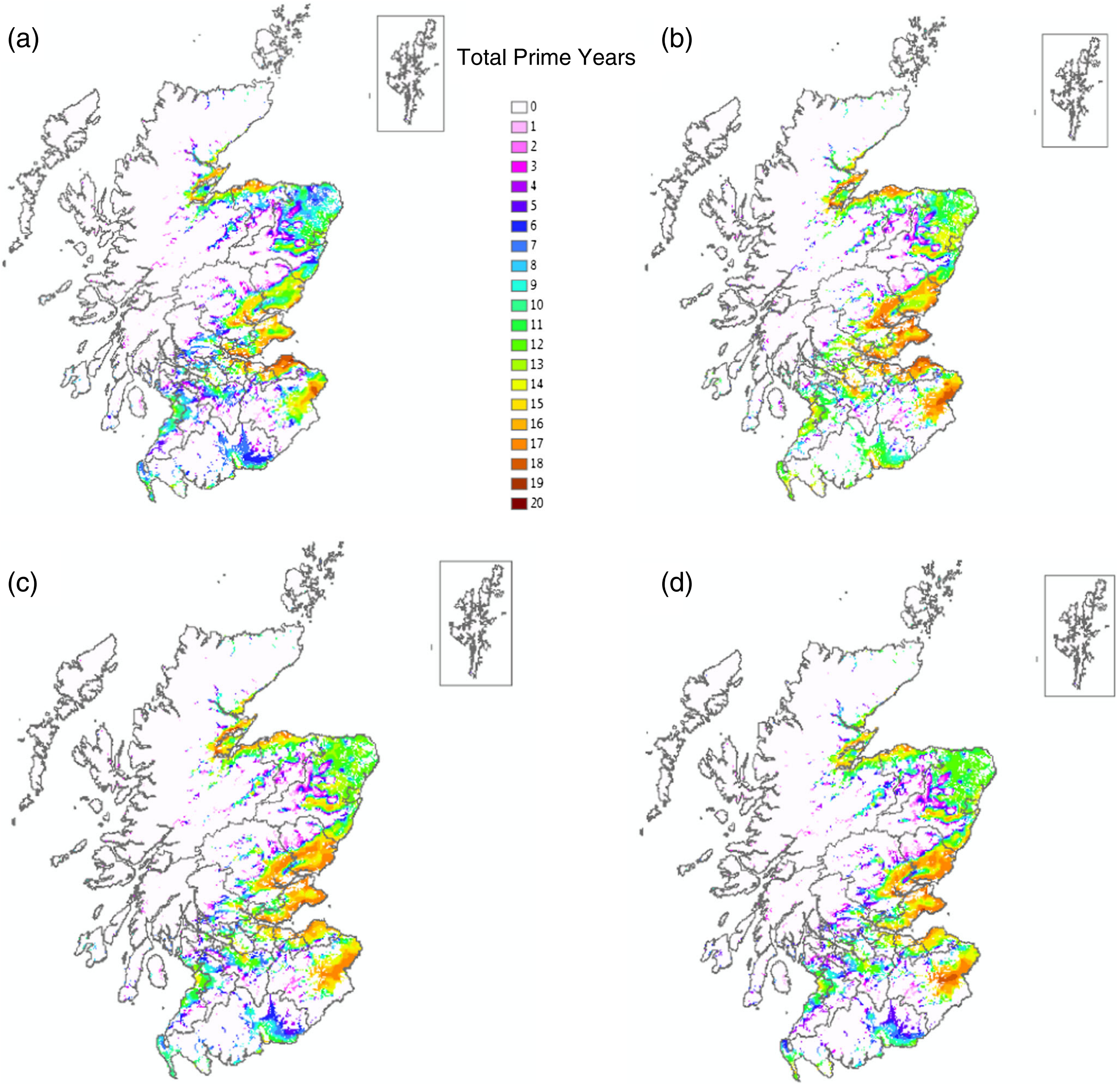


Fig. 6 Number of years classified as prime agricultural land during the reference periods **a** 1961–1980, **b** 1971–1990, **c** 1981–2000 and **d** 1991–2010

of variability in the WG simulations means that interpretation of baseline and future change requires caution. The range of simulation results for volatility also increases for the future, primarily because the minimum run value is lower, whereas the maximum run value remains similar to the baseline.

The plots of median simulations in Fig. 9 provide more information and show that across the paired sites, the difference in soil types has an important influence on the final combined soil–climate LCA. Sites with lower quality soils where the soil constraints dominate the final baseline LCA classification are less sensitive to the IAV caused by the climate. With the future 2050s' simulations, the general climatic improvement acts to reduce variability of land quality at many of the selected sites as the main constraint shifts from climate to soils, except in exceptional years, particularly on the poor-quality land. Beyond these general inferences, there is also a clear W–E difference in variability which is most apparent in the differences between south-west and south-east Scotland with a greater degree of variability in the west. There is less of a distinct pattern from N to S indicating that the primary influence on variability is not temperature (which varies mostly from N to S) but precipitation (which has a distinct W–E gradient) and its influence on soil moisture and hence LCA class.

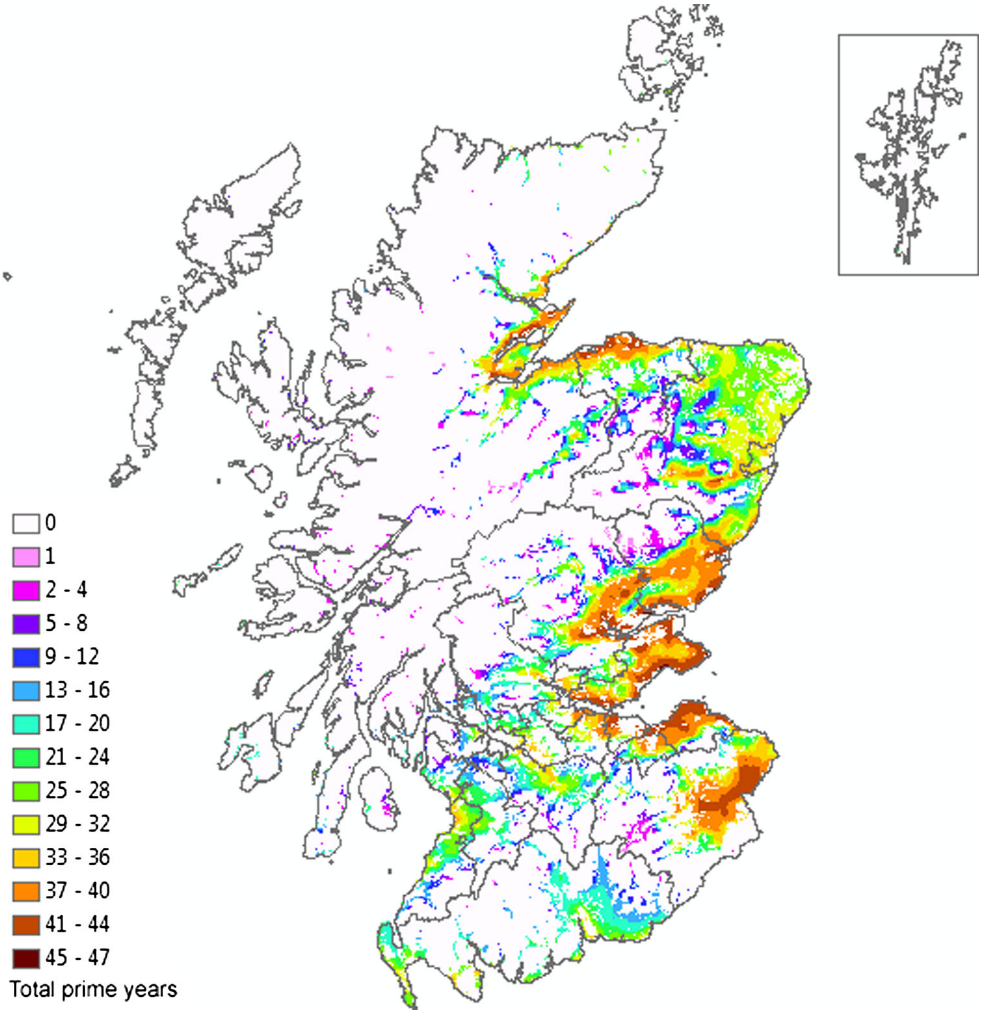


Fig. 7 Total years classified as 'prime' 1961–2011

Discussion

Results confirm that the inherently variable climate experienced in Scotland has important spatial and temporal variations that impact on land quality. Analysis of land quality and land-use potential through LCA has shown that IAV has both spatial and temporal dimensions, with the latter varying over multiple time periods meaning that there are also interdecadal changes. Therefore, although previous work has identified a long-term trend for an improvement in land capability (Brown et al. 2008, 2011), this trend is irregular and also subject to shorter term shifts that may act to confound its interpretation by land managers and planners. The interaction of decadal and interannual variability is particularly illustrated by the temporal changes in the volatility index (Fig. 8). However, recognition and interpretation of significant trends are confounded by the noisy time-series data. It has long been known that North Atlantic climatic variations often exhibit substantial short-term IAV superimposed on longer term trends (Helland-Hansen and Nansen 1920). Therefore, these decadal patterns may represent an aggregation of stochastic shorter term IAV patterns, as can happen with a random walk model, rather than the result of a deterministic process associated with anthropogenic climate change. These confounding issues have been particularly investigated for the North Atlantic Oscillation (NAO), a large-scale climatic phenomenon (Hurrell et al. 2003) that has an influence on many aspects of seasonal weather and its impacts in Western Europe, including land quality. These investigations have rejected the NAO as a random walk, with time-series analysis showing evidence of autocorrelation but with a dominant irregular component whose presence makes accurate forecasting problematic (Wunsch 1999; Stephenson et al. 2000; Mills 2004).

Regardless of the interpretation of temporal patterns of change, climatic variability has important impacts on land managers. The methodology described here can therefore be used to provide more objective results to investigate anecdotal reports of changing land conditions. This may be used to identify whether adaptive measures (e.g. changes in land use or management regime) may be considered robust in both

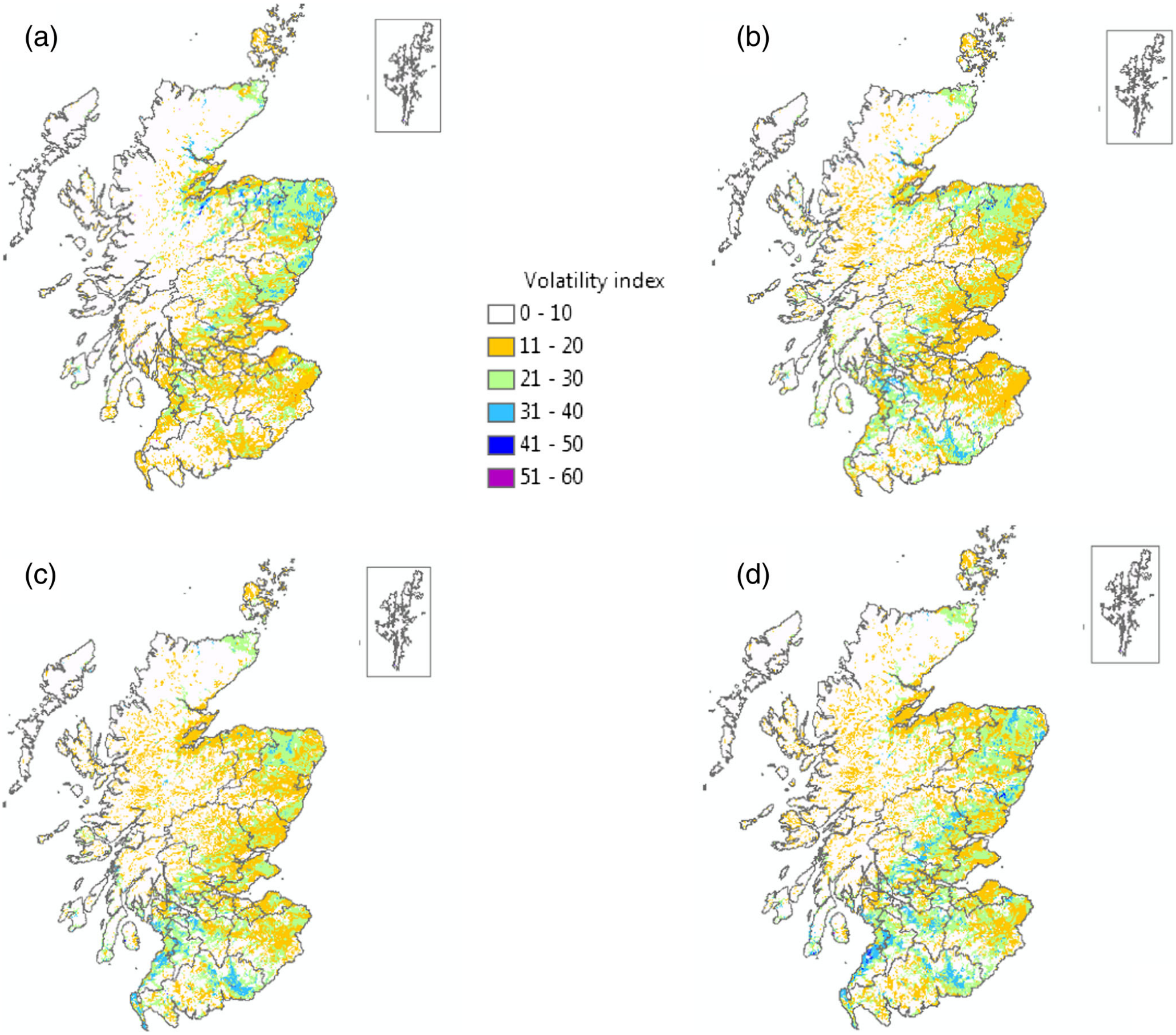


Fig. 8 Volatility of LCA class for **a** 1961–1980, **b** 1971–1990, **c** 1981–2000 and **d** 1991–2010

short and long term. For example, farmers in south-west Scotland have anecdotally reported difficulties in recent years with changeable conditions, and the analysis does suggest that variability has increased especially in this area. These difficulties have been associated with problems in farm planning from year to year. However, as similar patterns of variability occurred back in earlier periods (notably 1961–1980), then it may be appropriate to consider whether negative impacts are associated solely with changing IAV or other factors such as changing land management practices, including the use of heavier machinery, or shifts between spring and autumn sown crops, or both. In this context, it is worth highlighting that some crops are inherently more risky than others in their productivity and yields due to their sensitivity to seasonal weather patterns. This means that they have a greater sensitivity to IAV, resulting in optimum performance in good weather years but much weaker performance in poor weather years (Brown 2013). This may also be exacerbated by the increased specialisation on many farms and the shift towards monoculture in some locations. The negative consequences are particularly represented by very poor years when virtually no land in Scotland was defined as in prime condition, with resultant difficulties for land management and impacts on crop production. This has implications for food security, especially if these patterns are synchronous with those in other important crop-growing locations due to large-scale meteorological teleconnections. Previous research has not identified a statistically significant correlation between the bioclimatic metrics used for LCA classification in Scotland and the NAO (Brown 2013); however, work in England has identified a correlation for the NAO with the quality rather than the quantity of winter wheat yields (Atkinson et al.

Table 3 Changes in the volatility index for baseline and future periods at selected sites

Site	Period	WG volatility index median (min, max)	Observed volatility index
Cessnock	Control	22 (11, 36)	22
Cessnock	2050s	11 (0, 26)	–
Coull	Control	6 (2, 15)	12
Coull	2050s	0 (0, 4)	–
Halkirk	Control	10 (4, 22)	20
Halkirk	2050s	2.5 (0, 14)	–
Fans[a]	Control	0 (0,10)	10
Fans[a]	2050s	0 (0, 8)	–
Mauchline	Control	6 (0, 17)	17
Mauchline	2050s	0 (0, 14)	–
Tarland	Control	11.5 (5, 24)	21
Tarland	2050s	0 (0, 14)	–
Gordon[a]	Control	8 (2, 21)	16
Gordon[a]	2050s	0 (0, 14)	–

[a] Based upon 1,000 simulations

2005). Further investigation of the links between climate variability, land quality and food production would therefore be justified.

Most land evaluation techniques and established land capability systems are based upon static classification approaches (Rossiter 1996). By contrast, more dynamic approaches can acknowledge the importance of climate variability and change as key influences on land-use decision-making (Hudson and Birnie 2000; Brown et al. 2008). However, the question then arises as to how variability should be incorporated in conventional classification systems as there is currently no official guidance on this issue. This is a particularly important issue for land classified as ‘prime’ in Scotland because of its protected status in the planning system. In this case, a more simplified version of the volatility index, discriminating between prime (1) and non-prime land (0) and summing the difference over 20 years, may be used to identify a suitable limit for land that is too variable to be considered ‘prime’. In Fig. 10, areas that would be conventionally defined as prime land due to their long-term average but also have a prime/non-prime volatility index greater than 10 are highlighted; these are areas with more than 10 interannual transitions from prime to non-prime over the 20-year period. Such areas are usually in the geographic transition zone between prime and non-prime areas, therefore rather sensitive to the cut-off value chosen. Although a value of 10 would seem an appropriate cut-off, further work is required to ground this against current agronomic decisions and patterns of land use, reinforcing the empirical basis for land capability classification. Current evidence would suggest that the more variable locations, such as in south-west Scotland, traditionally prefer mixed cropping and grassland pasture systems for livestock production but that these traditions are also challenged by changing external drivers such as markets and policy initiatives (e.g. EU Common Agricultural Policy). The Less Favoured Area (LFA) scheme is a major component of EU Rural Development Policy aimed at supporting farming in areas with physical handicaps. Improved agro-climatic metrics have been advocated to better define LFAs (Schulte et al. 2012), although these are currently based upon the use of percentiles to capture variability rather than an equivalent volatility index as devised for the present study.

The present study has not yet incorporated the effects of drought risk which can affect some areas during otherwise good weather years when MPSMD values exceed 160 mm. Currently, this risk only covers small areas and is not a dominant influence on the standard classification using long-term averages, although it can be a land management issue in some years and is exacerbated by increasing demand for water for high-value crops (Brown et al. 2011). It is proposed that this issue could be further investigated through the adoption of a notional LCA class 0 to identify locations where soil moisture deficits exceed available soil water capacity. This can then be included in the volatility index to identify the risk of excessively dry conditions in addition to the currently dominant wetness factors. Similarly, the local interaction of climate, drainage and excessive soil moisture may provide variable site constraints that extend beyond the present analysis. Further refinement of the LCA system to specifically include actual soil moisture values rather than potential values would therefore provide a closer measure of land-use potential.

Analysis of future climate change has tended to emphasise issues related to shifts in average climatic conditions rather than variability, although statements are regularly made from a theoretical basis on prospective changes in variability and the implications for more extreme conditions. A cautious approach should be dictated by the limitations of climate models to reliably represent patterns of shorter term variability, notably those influenced by large-scale coupled ocean–atmosphere phenomena such as the NAO or El Niño Southern Oscillation (ENSO) (e.g. Handorf and Dethloff 2012; Davini and Cagnazzo 2013). In the present study, the importance of local influences on IAV suggested the use of a WG at different locations. The results imply that the dynamic spatiotemporal interaction of climate variability with other influences on land quality, notably soil properties, may produce a rather different pattern of resource availability than occurs at present. This has particularly important implications for marginal agricultural locations, where if good soils are available, and variability does not increase, then new opportunities may be available. This relaxation of climatic constraints will have a geographic dimension that is subject to considerable uncertainty but would appear to favour eastern Scotland. However, the WG simulations need to be interpreted cautiously due to

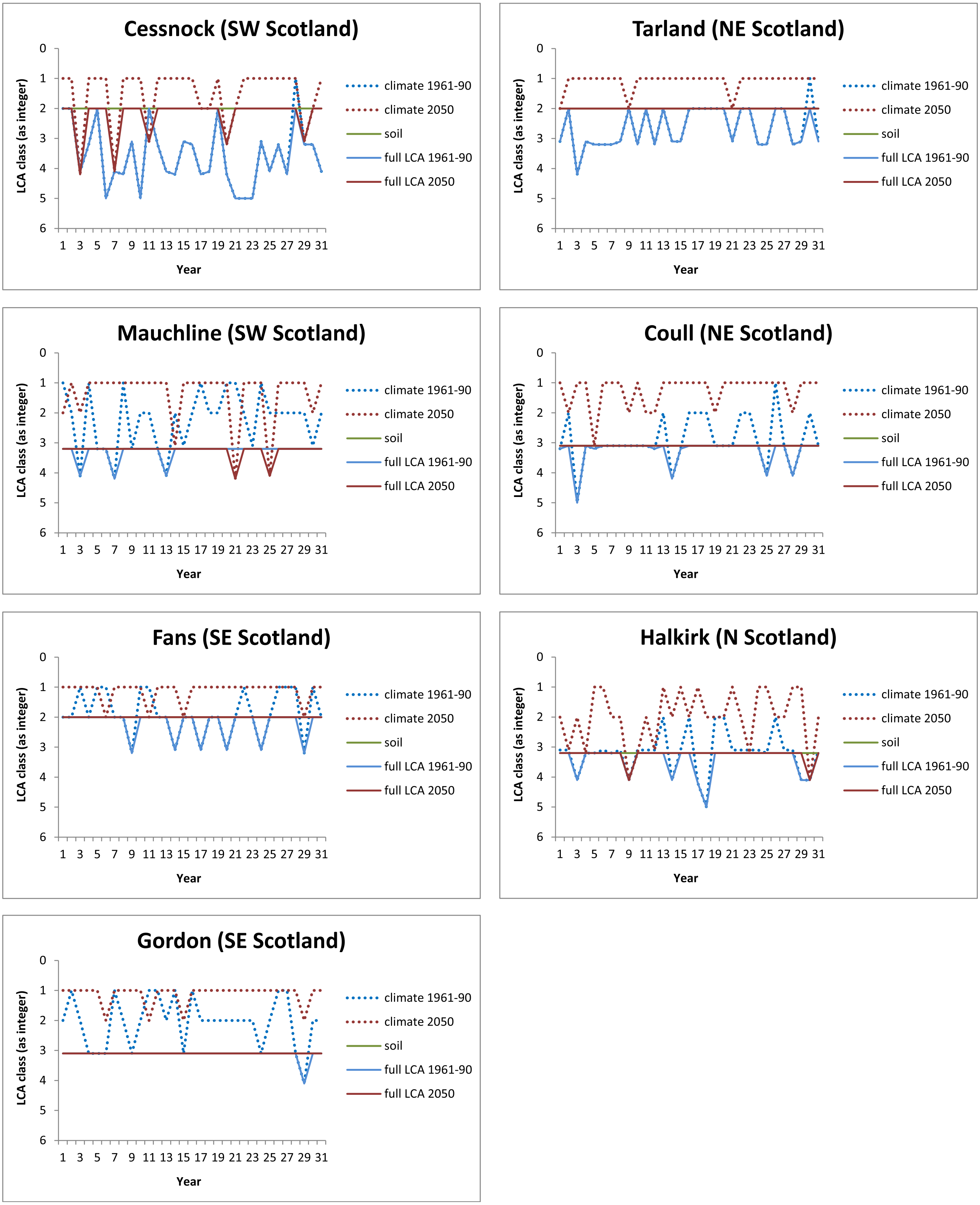


Fig. 9 Median WG simulation runs at the selected sites for the control period and future 2050 scenario. Diagrams using the same schema as Fig. 3 to illustrate final LCA class assignment (*solid line*) based upon the greatest constraint (lowest class) of contributing soil and climate classes

the increased spread of simulations for the future period and the tendency for them to underestimate variability compared to observed data. The WG is also restricted because the same statistical relationships are assumed to apply for the future and

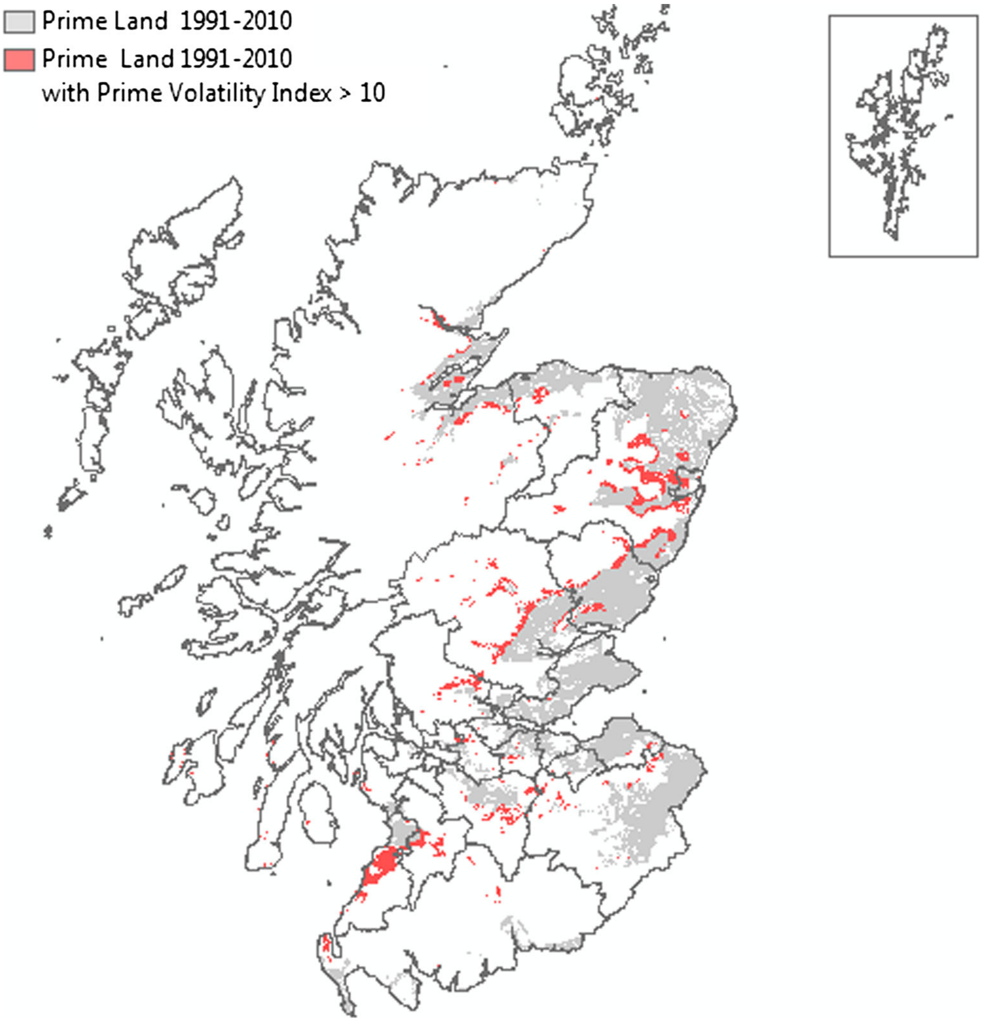


Fig. 10 Prime agricultural land 1991–2010 which also has a high prime volatility index

due to the lack of explicit controls on autocorrelation when aggregating multi-year sequences, which may mean that longer term variability may not be well represented by the UKCP09 WG (Jones et al. 2009). Dynamic downscaling approaches (notably regional climate models) may therefore potentially provide a more robust assessment of changes in IAV but are currently limited in their ability to represent both shorter term variability and local spatial variations. Another alternative may be provided by other types of WGs that use hierarchical or weather-typing approaches (e.g. Wilby et al. 2002), but this requires further comparative investigation.

Conclusion

Analysis of IAV of land capability classes in Scotland shows that there are significant spatial and temporal variations in land quality and in the volatility between LCA classes from year to year. These patterns complement dynamic shifts in long-term averages but provide additional shorter term information that highlight changing opportunities and constraints for land managers and planners. Analysis of changes over the last 50 years shows that some locations have experienced a general improvement in capability and with reduced volatility, notably north-east Scotland. By contrast, over the same period, other locations have experienced more variable decadal patterns of variability, including evidence of increased volatility in the most recent decades, notably south-west Scotland. A WG-based analysis of future changes in IAV suggested that there will be complex spatiotemporal interrelations between climate variability and local soil properties that will influence land quality. The influence of a changing climate on these patterns of shorter term variability (interannual and decadal) remains a major source of uncertainty, but it is highly likely that patterns of variability will continue to change. The WG used for the future analysis has restrictions that only allow cautious inferences, including the wide variation amongst climate models used to drive the simulations. However, although no increase in IAV could be established, some support is provided that IAV will be greater in west Scotland compared to east Scotland. For areas with good agricultural soils, these patterns of IAV will be an important influence on the scope for land-use intensification, whereas areas of lesser quality soils will remain constrained by these intrinsic properties. Transitional areas between the uplands and lowlands represent the zones of greatest uncertainty, as these have the greatest temporal and spatial variability across LCA classes at present.

These results have implications for agricultural management systems, which traditionally have developed to cope with yearly variability. A trend to increased intensification, including detailed scheduling of activities and a goal of optimised crop yields, may be challenged in those areas that experience high or increasing volatility of IAV. More robust practices that are adapted to a variable climate and which accept sub-optimal productivity in good years, in return for adequate performance in poor years, may be preferable to a more risky optimisation strategy that leads to large variations in productivity from year to year. In some locations, high volatility may imply that areas defined as prime land due to their average conditions may need to be reclassified as 'sub-prime' as these average conditions rarely prevail, and the use of an average masks considerable variation from year to year.

Agriculture is particularly sensitive to these shorter term variations, and the conventional emphasis on longer term average changes in climate change studies has meant that these influences have often been overlooked in the design of suitable adaptation strategies. In some circumstances, this requirement for robust adaptability due to fundamental limits on climate 'predictability' (Hallegatte 2009) is being overridden by economic pressures for specialisation to meet the increasing demands of global markets. The role of proactive flexible strategies, as opposed to reactive post-event adjustments, is particularly pertinent, but this requires availability of relevant information for land managers. Dynamic land capability classification and mapping provide a tool to stimulate this dialogue and facilitate wider knowledge exchange.

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