Vol. 37: 43–57, 2008
doi: 10.3354/cr00753

CLIMATE RESEARCH
Clim Res

Printed September 2008
Published online August 19, 2008

Influence of climate change on agricultural land-use potential: adapting and updating the land capability system for Scotland

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ABSTRACT: Land capability systems have been designed to evaluate and communicate biophysical constraints on land use, including climatic limitations. By grading land quality, the resulting information is particularly relevant for planners and managers, and for land valuation. Higher-grade land is more flexible and has more options for land use. Using Scotland as a case study, a widely-used land capability system was adapted to investigate the influence of recent and future climate change on land-use potential. The adapted method was applied to both interpolated gridded weather station data and to future climate change scenarios derived from the HadRM3 climate model. At a national scale, differing regional patterns of land capability were recognised, with changes in these patterns occurring in recent decades and projected to occur on a more substantial scale into the future. In general, climate change is acting to enhance land-use potential in Scotland, mainly in the drier east, while the west remains constrained by its wetter climate. These results demonstrate the key control directed by soil moisture values on land-use options, in addition to temperature change. Shifts in land-use potential have implications for both strategic resource planning and for developing anticipatory climate change adaptation actions. The land capability assessment highlights not only potential changes in agriculture and other productive land uses, but also repercussions for biodiversity and terrestrial carbon stocks. Various amendments are suggested to the land capability procedures to reflect existing or emerging climate-related issues that were not considered necessary in the original system, notably excessive soil moisture deficits.

KEY WORDS: Land capability · Land suitability · Agriculture · Climate change · Soil moisture · Accumulated temperature · Land-use change

1. INTRODUCTION

With growing global human populations and increasing exposure to climate change, there is wide acceptance that human well-being is linked to land use that can sustain a diversity of ecosystem services (Millenium Ecosystem Assessment 2005). Nations are therefore having to re-evaluate how they retain high levels of agricultural food production while balancing other demands from land such as maintaining good drinking water quality, limiting greenhouse gas emissions or safe-guarding the social and economic benefits of their landscapes.

The land capability approach (sometimes also referred to as 'land suitability') identifies the potential to use an area of land for different purposes or management practices. Although the original system was devised for farm planning in the USA (Klingebiel & Montgomery 1961), land capability classification is adaptable and can be tailored to particular land-use requirements. Furthermore, as the approach is intrinsically uncomplicated, and the information can be presented in a straightforward and non-technical manner, land capability has gained wide acceptance and adoption across a range of users, including planners, land managers and farmers. Various classification systems

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for agriculture and forestry are now in common use worldwide (FAO 2007).

Land capability classification is based upon intrinsic biophysical limitations of the land, i.e. those that cannot be removed or ameliorated by reasonable management, and therefore act as constraints to use. Higher-grade land has more options for use, therefore demonstrating a greater flexibility; land of a particular capability class also has the potential to be used as specified for any lower classes. Therefore, land capability systems can identify both the capacity of an area of land for different uses and also the optimal use from a biophysical, as opposed to socio-economic, perspective. As a consequence, land capability classes can provide a rational basis for land-use planning and the most favourable utilisation of land resources (FAO 1993).

Climatic constraints are key metrics of most agricultural land capability systems, either by restricting ecological processes such as plant growth rate, or by limiting management activities, especially those related to the timing of specific practises, such as ploughing, sowing or harvesting. These climate metrics are an important link between prevailing meteorological conditions, as measured at weather stations, and their specific relevance for land-use activities (Stone & Meinke 2006). A change in climatic constraints implies that new opportunities for, or risks to, land use could become manifest, based solely on the intrinsic conditions. Therefore, exploration of climate change impacts on land capability can identify areas where the *range* of options is changing or may be expected to change in the future, and explicitly whether this inherent flexibility in land-use options is increasing or decreasing. This information can then provide the platform from which to explore the social and economic implications of climate change, alongside other pressures and drivers, by scoping individual perceptions and experiences against the potential land-use responses. A land capability approach therefore emphasises the practical implications of climate change on land-use potential for farmers, land managers, planners or other stakeholders.

In this study, we investigated recent and future climate change through the Land Capability for Agriculture (LCA) classification developed for the UK and widely used in Scotland (Bibby et al. 1982). Although Hudson & Birnie (2000) demonstrated that the LCA is quite sensitive to climate variability, they did not consider the consequences of long-term climatic trends. Here we firstly update the LCA methodology, and secondly investigate the stability of the LCA system against trends in recent and future climate change, with particular reference to the extent of high-grade ('prime') agricultural land. Scotland has wide regional variations in both climate and land quality, together with a high proportion of carbon stocks in organic soils. The planning and management implications of any changes therefore make it a highly suitable case study. However, the general methodology is adaptable and could also be applied to many other countries, especially as the FAO has recognised the need to update its guidance on land evaluation with regard to climate change and broader environmental services (FAO 2007).

As the original LCA method was empirically grounded in fieldwork and then subsequently manually transferred onto maps, an important prerequisite of the present study was to develop an updated digital method that could replicate the key features of the original method in a robust and replicable format. This new method was then applied to the same agro-climatic metrics as the original LCA using spatial interpolation procedures in a Geographical Information System (GIS), incorporating both present-day observational data and future climate change scenarios to produce new LCA maps.

2. LAND CAPABILITY FOR AGRICULTURE (LCA) SYSTEM

The land-use capability system was adapted for agriculture in the UK by the pioneering work of Bibby & Mackney (1969) and subsequently developed into the LCA system of Bibby et al. (1982). The LCA approach can de defined as a static spatial method because it considers geographic variation in climatic (and other) parameters in a stationary, rather than temporally dynamic, state (cf. Rossiter 1996). LCA was explicitly intended to be interpretative rather than to follow a rigid application of rules, with a series of guidelines designed to produce uniformity at the national scale.

The LCA framework includes climate and soil property constraints along with related factors such as gradient and local soil–climate interactions (e.g. wetness, droughtiness and erosion potential). For climate, it uses a 2-parameter array classification based upon accumulated temperature and maximum soil moisture deficit (Birse & Dry 1970); the classification can also be modified locally by wind exposure and aspect if necessary. Seven major classes are distinguished (Table 1), each assuming a 'satisfactory level of management' appropriate for that class (Bibby et al. 1982). Two of the classes were recognised as having climatic subdivisions ($3_1/3_2$ and $4_1/4_2$) based upon the degree and variability of limitation on crop type. Each class was defined by the 2 key climate parameters, with the boundaries between classes derived from a combination of empirical field evidence and expert judgement (Fig. 1; Bibby et al. 1982). The primary climate parame-

Table 1. LCA classes defined by Bibby et al. (1982) and associated land uses

Class	Category	Climate limitations	Land use
1	Prime	None or very minor	Very wide range of crops with consistently high yields
2	Prime	Minor	Wide range of crops, except those harvested in winter
3_1	Prime	Moderate	Moderate range of crops, with good yields for some (cereals and grass) and moderate yields for others (potatoes, field beans, other vegetables)
3_2	Non-prime	Moderate	Moderate range of crops, with average production, but potentially high yields of barley, oats and grass
4_1	Non-prime	Moderate–severe	Narrow range of crops, especially grass, due to high yields but harvesting may be restricted
4_2	Non-prime	Moderate–severe	Narrow range of crops, especially grass, due to high yields but harvesting may be severely restricted
5	Non-prime	Severe	Improved grassland, with mechanical intervention possible to allow seeding, rotavation or ploughing
6	Non-prime	Very severe	Rough grazing pasture only
7	Non-prime	Extremely severe	Very limited agricultural value

ters are defined in the following sub-sections, with a final sub-section outlining the original LCA implementation.

2.1. Accumulated temperature (AT0)

As solar radiation data are only available from very few sites, a more representative indicator of the amount of energy available for crop growth is provided by AT0. This parameter is produced by summing mean daily temperature values above the threshold value of 0°C to provide a monthly aggregate in degree-days. Although a value of 5.6°C is more often used for a growing degree-days threshold, Bibby et al. (1982) used the lower value in LCA because of the small but significant leaf growth in both cereals and grass occurring at lower temperatures down to 0°C. The LCA metric was also restricted to AT0 for the first 6 mo of the year (January–June inclusive) because of its critical role in leaf growth, and to exclude the potentially detrimental effects of higher temperatures in the latter half of the year. To avoid the possible distorting effects of extreme years on the climatic 'norm', the lower quartile AT0 value from the reference time period was used as the parameter value.

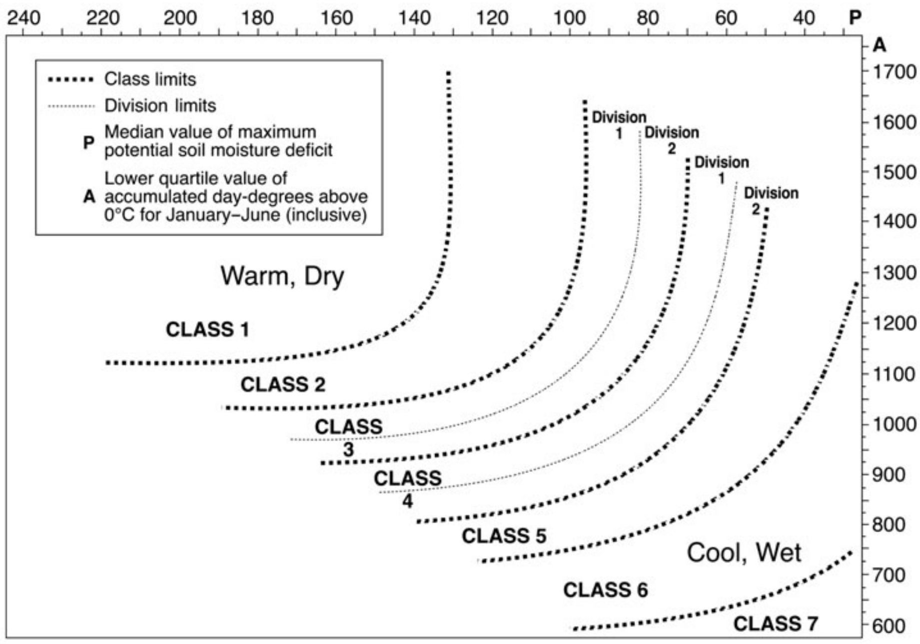

Fig. 1. The 2-parameter climate classification for LCA classes (figure from Bibby et al. 1982)

2.2. Maximum potential soil moisture deficit (MPSMD)

This parameter reflects the impact on soil moisture levels of the balance between precipitation and evaporation over 1 yr. Typically, soils dry out 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 a potential evapotranspiration (ET_0) function, therefore assuming an unlimited supply of water from the soil. This provides a reference value of potential deficit rather than the actual deficit, which would often be lower but would also vary with soil conditions. MPSMD is the maximum potential deficit during 1 yr and was chosen by Bibby et al. (1982), as it provided a reliable indicator of the amount of time when the land is unsaturated and therefore in a workable condition, a key measure of land-use flexibility. The original LCA classification for Scotland used ET_0 data derived from meteorological stations via the Met Office Rainfall and Evaporation Calculation System (MORECS; Thompson et al. 1981) based upon the Penman (1948) method, but MORECS has subsequently been revised and updated (Hough & Jones 1997) and is therefore no longer completely compatible with the original data. To remove the potentially distorting effects of extreme years in the LCA classification, MPSMD is represented by the median value from the climate reference period.

2.3. Original implementation of LCA

The climate reference period used for the original LCA was 1958–1978 except for wind data, which were derived from a shorter period, 1965–1973. By supplementing the maps of Birse & Dry (1970) with additional data, a hand-drawn map of Climatic Guidelines was produced for Scotland. These guidelines provided a key evaluation stage by identifying the highest possible LCA class for an area based solely on climatic constraints. These constraints were then combined with the other limitations, derived from the National Soil Survey of Scotland (Macaulay Institute for Soil Research 1984), to produce the final delineation of LCA classes. Two phases of mapping were implemented in Scotland: the first was nationally at 1:250 000 scale in 1981, followed by a later phase in 1987 at 1:50 000 scale to cover improved agricultural land and the adjacent upland fringe. For planning purposes, particularly in relation to built development, the LCA classes were reduced to 'prime' and 'non-prime' land (Table 1; Scottish Development Department 1987), with the underlying principle being that the highest-grade agricultural land should be protected where possible. By implication, if other factors such as soils and topography are favourable, areas defined as 'prime' land would be expected to be most likely used as arable land, and this is supported by a comparison to the 1988 Land Cover of Scotland dataset (MLURI 1993) although some lesser quality land is in fact also arable (Fig. 2). The LCA system has become embedded within land-use planning policy and practise in Scotland and, although some planning regulations have now been relaxed, it remains a significant factor in strategic decision making.

3. DATA AND METHODS

3.1. Recent climate data

The reference period for the LCA climate constraints was updated using 1961–2000 data derived from a standardised monthly climatology produced by the UK Met Office (UKMO) for the UK Climate Impacts Programme (UKCIP). This climatology was developed from quality checks of all available observing station records and based upon a multiple regression method incorporating geography and elevation with coastal and urban effects, followed by distance-weighted spatial interpolation onto a 5 km grid (Perry & Hollis 2005b). Typically, the density of stations used in the production of these data was reported as 150 to 200 per 100 km^2 for rainfall data and 15 to 30 per 100 km^2 for other meteorological data (Perry & Hollis 2005b). As wind speed data were only available from 1969 onwards, the missing years from 1961–1968 have been substituted with the monthly mean value from 1969–1980 within our subsequent LCA analysis.

3.2. Future climate data

Future LCA climatic constraints were based upon data constructed for the UKCIP02 climate change scenarios (Hulme et al. 2002). These scenarios have been derived from dynamic downscaling of the Hadley Centre global climate model (GCM) HadCM3, through an intermediate atmospheric model and then a 50 km regional climate model (RCM), HadRM3. The RCM was run under both present atmospheric conditions from 1961–1990 and also a forcing scenario of increased greenhouse gas emissions from 2071–2100 following the Intergovernmental Panel on Climate Change A2 socio-economic scenario pathway (IPCC 2000). From the A2 scenario, Hulme et al. (2002) used pattern-scaling to adjust the RCM outputs for other emissions scenarios and time periods, allowing UKCIP02 to provide high-resolution (50 km) datasets for 4 IPCC scenarios (A1FI, A2, B2, B1; termed 'High

Fig. 2. Areas of (a) 'prime' land defined for Scotland by the original LCA (1:250 000 scale) with climate data from 1958–1978 and (b) arable land defined by the Land Cover of Scotland project in 1988

Emissions', 'Medium High Emissions', 'Medium Low Emissions' and 'Low Emissions', respectively) for the years 2011–2100. Together, the UKCIP02 scenarios imply a general shift to drier summers and wetter winters for the UK, although with significant regional variation (Hulme et al. 2002).

For the present study, a simple interpolation ('Δ-change method') was used to downscale the future climate scenarios onto the same 5 km resolution grid as the observed baseline datasets, thereby maintaining a consistent scale of analysis and allowing some correction for biases in the raw model data. This interpolation used the relevant change value derived from the RCM between the simulated baseline period (1961–1990) and the future time period, which was then used to increment the observed baseline data at a 5 km scale. For each climate parameter, the absolute change value was used (e.g. +1.5°C for temperature change), except for precipitation amounts, which were based on percentage changes (e.g. –12%) to allow for local topographic variation. This simple interpolation is rapid and suited to multiple variables, although it should be noted that sub-50 km scale variability represents only the spatial variation in the baseline rather than providing an indication of how these local differences might vary in the future. The downscaling and interpolation procedure also allowed the re-adjustment of climate model 'monthly' data (for the HadRM3 data, 1 yr is composed of 12 mo each of 30 d) into calendar months, again to facilitate a common mode of analysis.

3.3. Derivation of LCA climate constraints

To replicate the original LCA method, the gridded climate datasets were integrated within a GIS and a series of routines developed to calculate the required LCA parameters. The 2 main parameters used to define LCA were calculated on a cell-by-cell level across the grid as described in Sections 3.3.1 and 3.3.2.

3.3.1. AT0

AT0 data for January–June were calculated yearly in degree-days using monthly mean temperature data. Multiplying the mean temperature by the number of days in that month produced an accumulated monthly temperature (except where the monthly mean was less than 0°C, as this was equated to an AT0 of 0), which was then summed for each half-year. Following the original procedure (Bibby et al. 1982), the lower quartile value from the sequence of years was derived for the LCA classification. The same procedure was applied to both observed and future climate datasets.

3.3.2. MPSMD

Potential soil moisture deficits were derived from precipitation and potential evapotranspiration (ET_0). Precipitation data were directly available from the UKMO/UKCIP observed climatology and UKCIP02 scenarios, but ET_0 had to be indirectly calculated from other available data. For the present study, ET_0 (mm d^{-1}) was estimated using the Food and Agriculture Organisation (FAO) recommended version of the Penman-Monteith (PM) method for a reference surface of grass (Allen et al. 1994a):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma(900/[T+273])u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (1)$$

where R_n is net radiation at the crop surface (MJ m^{-2} d^{-1}); G is soil heat flux density (MJ m^{-2} d^{-1}); T is air temperature at 2 m height (°C); u_2 is wind speed at 2 m height (m s^{-1}); e_s is vapour pressure of the air at saturation (kPa); e_a is actual vapour pressure (kPa); Δ is the slope of the vapour pressure curve (kPa $°C^{-1}$); and γ is the psychrometric constant (kPa $°C^{-1}$).

The methodology used associated FAO procedures to calculate the necessary ET_0 parameters from standard meteorological datasets (Allen et al. 1994b), requiring data on net radiation, maximum temperature, minimum temperature, wind speed and vapour pressure. With the exception of net radiation, these data were available from the UKMO/UKCIP baseline climatology (Perry & Hollis 2005b). Wind speed data were adjusted from 10 m observational height to 2 m height, as required by Eq. (1), using a standard height–speed logarithmic relationship above a grass surface. Net radiation (the surface energy balance between net short-wave radiation and net long-wave radiation) were derived from the FAO formula (Allen et al. 1994b) linking radiation with the sunshine duration data available in the UKMO/UKCIP climatology, based upon the adaptation and empirical calibration of conventional short-wave (Ångstrom 1920, Prescott 1940) and long-wave radiation formula (Brunt 1932). Soil heat flux, i.e. the small proportion of radiation absorbed by the surface that acts to warm the substrate (depending on season), was estimated based upon monthly mean temperatures in the formula $G = 0.14 \times$ (current month – previous month) (Allen et al. 1994b).

To derive MPSMD, the difference between precipitation and ET_0 was calculated and accumulated as a deficit on a monthly basis, with yearly analysis to determine the maximum value. However, as the monthly data only provide end-of-month values, the maximum daily deficit, as used by the original LCA, could be larger. Therefore, a second-order polynominal regression equation ($R^2 = 90.5\%$) linking daily to monthly MPSMD was derived from MORECS weather station data for each month from 1961–1980, allowing daily MPSMD to be derived. Finally, to be consistent with the original LCA method, long-term averages were produced using the median value. The same procedures were used with the climate model data for the future LCA assessments, although here net radiation data were directly available from the model whereas vapour pressure had to be indirectly determined from relative humidity data.

3.4. Replication of LCA class boundaries

The original class boundaries (Fig. 1), rather than define rigid thresholds, allow higher values of AT0 to compensate for lower values of MPSMD and vice versa (Bibby et al. 1982). The same principles were replicated in the updated methodology, using regression equations where necessary to re-establish the original relationship between AT0 and MPSMD. These boundaries were then used to classify the new climate parameters on a cell-by-cell basis across the 5 km grid by comparing actual values against those required for a particular LCA class. The final map classification was based upon identifying the highest LCA class that a particular cell could attain for the relevant time period. Following the original LCA, data were aggregated and analysed in 20 yr time periods.

3.5. Adding soil and topographic constraints

Rigorous re-assessment of the other LCA constraints is beyond the scope of this paper, especially due to the complexity of soil–climate interactions. However, there are some intrinsic soil and topographic properties that ensure the land would never become 'prime' agricultural land (LCA class 3.1 or better) even with extreme climate change scenarios. By integrating both soil unit data from the Soil Survey for Scotland 1:250 000 maps and slope data from 1:50 000 topographic maps with the future LCA climate data, it was possible to 'mask out' areas with unsuitable soil components and limiting topography. For prime agricultural land, a series of key constraints were identified.

(1) Topography. Slopes >7°, which tend to impose restrictions on the use of machinery and constrain options.

(2) Soil depth. Soils with an effective rooting depth less than 45 cm due either to bedrock or impenetrable subsoil.

(3) Soil wetness. Some soils have intrinsic soil moisture retention properties that would prevent them from ever becoming 'prime' land. While most of these

are highly organic uncultivated soils (including blanket peat), some poorly drained mineral soils (wetness class IV in the Soil Survey) were also excluded.

(4) Soil pattern. Some areas of land are inherently variable in quality, e.g. where the intricate pattern of freely and poorly drained soils make their integrated management very difficult.

(5) Soil stoniness. Some soils, e.g. those developed on fluvioglacial gravels, are inherently stony: a 35% maximum stoniness criterion was therefore applied.

At the local scale, soils and topography are the key spatial discriminators of LCA; therefore, during the masking process, a common resolution of 1 km was maintained for the combined analysis.

4. RESULTS

Results are described for the 2 primary LCA climate parameters and then in terms of the potential changes in 'prime' agricultural land constrained by these climatic parameters. With regard to the future projected changes, indicative results are presented for the UKCIP02 scenario, Medium-High Emissions (IPCC A2), for the 2050s period (2046–2065); results for other scenarios are available in CR Supplementary material at www.int-res.com/articles/suppl/c037p043_app.pdf.

4.1. Recent changes in AT0

As expected from previous work (e.g. Jones & Lister 2004, Barnett et al. 2006), lower-quartile AT0 predominantly exhibited an upward trend from 1961–1980 to 1981–2000 (Fig. 3a). However, the pattern of change showed some interesting regional differences. Areas in eastern Scotland have experienced the largest increase for January–June (by >50 degree-days), whereas western Scotland has tended to experience a less significant rise. Furthermore, some upland areas and part of the Western Isles have apparently actually experienced a decrease in AT0 degree-days. To place these changes in context, it is also pertinent to consider changes in the upper-quartile AT0 between 1961–1980 and 1981–2000. This reveals a rather different pattern (Fig. 3b): all areas show an increase in AT0 degree-days but the magnitude of this increase shows a north–south gradient, with the changes becoming progressively larger toward the south. Hence, although these results are consistent with the reported warming trend, they indicate that for the half-year critical for crop growth, the trend has been more sustained in the south and east of the country, and especially pronounced in a few particularly warm years in the south.

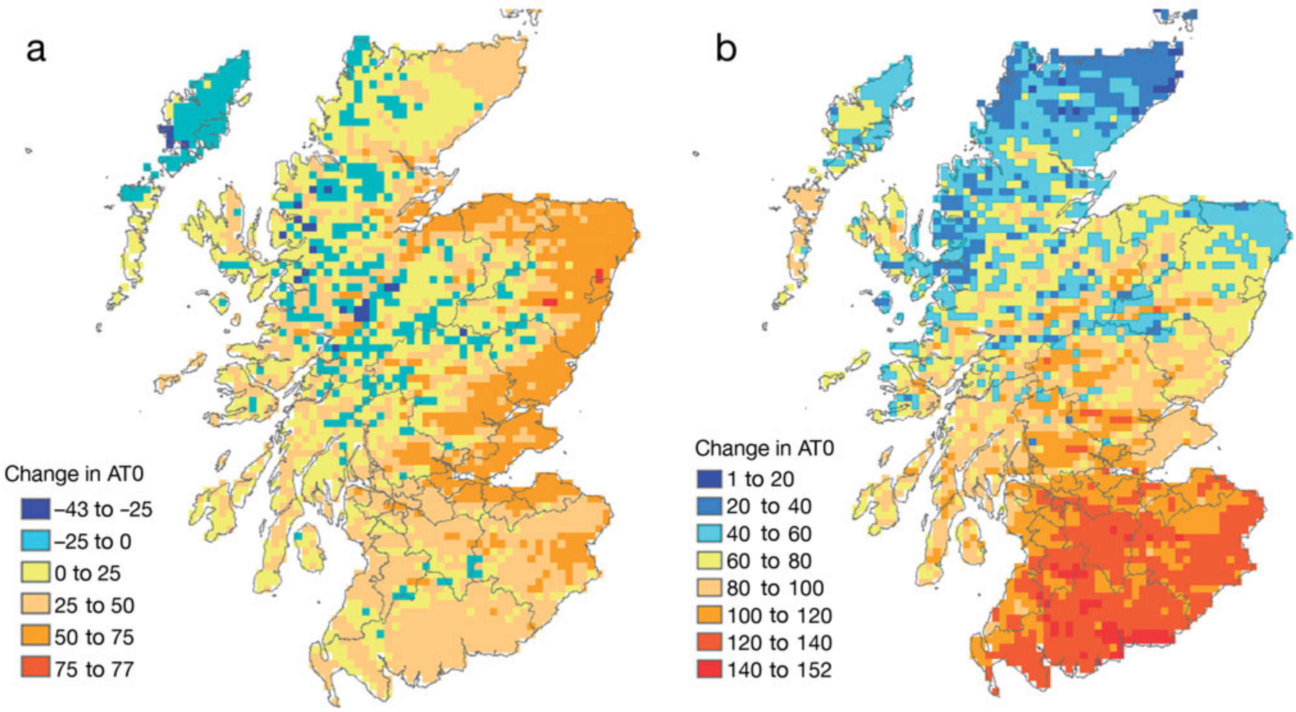

Fig. 3. Changes in AT0 (in degree-days) for Scotland between 1961–1980 and 1981–2000 using (a) lower quartile and (b) upper quartile

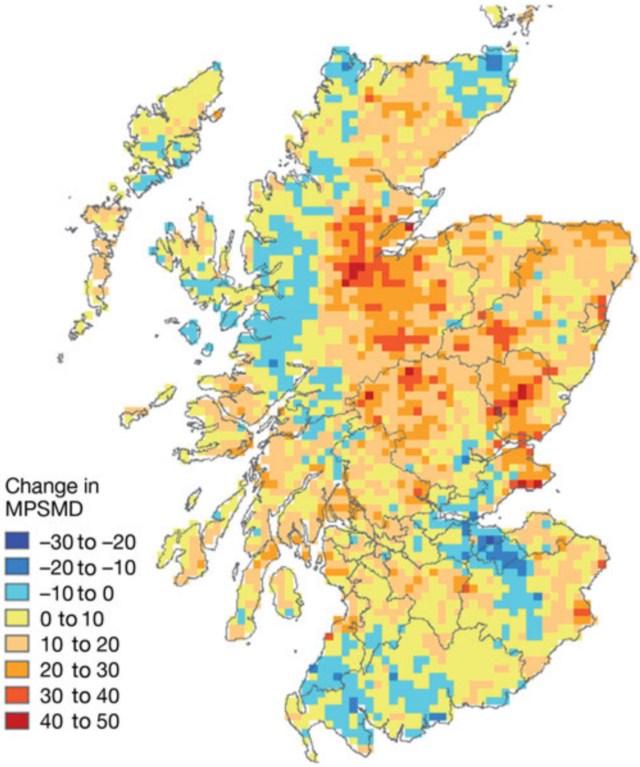

Fig. 4. Changes in median MPSMD (in mm) for Scotland between 1961–1980 and 1981–2000

4.2. Recent changes in MPSMD

Firstly, to validate the calculated ET_0 datasets, mean values for 1961–1980 were compared to the independent summary data provided by Francis (1981), which were also used in the original LCA. Despite the high level of empirical adjustment, no significant spatial anomalies were evident between the 2 datasets (within a range of ±10%), suggesting that the new method was reasonably consistent with the original method.

Fig. 4 shows changes in median MPSMD between 1961–1980 and 1981–2000, as consistent with the original LCA procedure. A reduction in MPSMD has occurred for parts of western Scotland, whereas an increase in MPSMD developed throughout much of eastern Scotland. Although ET_0 rates have tended to rise in most areas due to an increase in radiation and temperature, the influence on soil moisture deficit has been varied due to shifts in regional precipitation patterns that have occurred during this period. In general, the west has become wetter and the north-east has become drier, a trend also detected in other studies (Perry & Hollis 2005a, Barnett et al. 2006). As the predominant direction of moisture import is from the west, this suggests that the orographic 'rain shadow' effect has acted to further shelter many eastern areas. Noteworthy exceptions to this general pattern occur around the Forth estuary (central-east Scotland) and Caithness (north Scotland), which may be related to the lack of high ground to the west of these areas allowing precipitation to penetrate eastwards. However, the changes in MPSMD around the Forth estuary represent only a small reduction for an area with consistently high values of MPSMD throughout 1961–2000.

4.3. Recent changes in LCA 'prime' land

Combining AT0 and MPSMD allows an investigation of changing climatic constraints on the LCA. Areas of agricultural 'prime' land (Fig. 2a) identified by the original LCA classification (with climate data for 1958–1978) can be compared to the updated climate results for 1961–1980 and 1981–2000 (Fig. 5a,b). In both cases, areas of unsuitable soils and topography were masked out following the procedure in Section 3.5.

As may be expected, areas of 'prime' land defined with the new method for 1961–1980 (Fig. 5a) are similar to the distribution of 'prime' land in the original LCA. The main exception is in north-east Scotland where the climatic constraints for 1961–1980 have apparently significantly reduced the area of 'prime' land. Whether this difference is climatic or methodological (e.g. related to variations in the source data or data processing) is difficult to establish because the original LCA method used material that is now unavailable. Minor differences between results, even for the same time period, could be attributable to the original method having used site-based manual interpolation, whereas the revised method uses digital interpolation based upon 5 km grid cells. However, it can be noted that Hudson & Birnie (2000), using site data, found that using the reference period 1961–1980 tended to move many stations to cooler, wetter conditions than when they were classified under the original 1958–1978 period LCA. As much of north-east Scotland was originally defined as LCA class 3_1, it is therefore plausible that this has dropped a class for 1961–1980 and has thus become 'non-prime' land.

The LCA map for 1981–2000 (Fig. 5b) exhibits some subtle changes by comparison to that for 1961–1980. Notable increases in the area of 'prime' land occur, particularly in east and north-east Scotland. By contrast, it seems that in most western areas, the decreased MPSMD is compensated for by an increase in AT0, thereby maintaining a similar small amount of land classified as 'prime' there. Hence, overall, Scotland has gained in potential high-grade agricultural land.

Fig. 5. Areas of 'prime' land in Scotland based upon updated LCA climate constraints for (a) 1961–1980 (b) 1981–2000

4.4. Future changes in AT0

Projected changes in lower-quartile AT0 by the 2050s time period are shown in Fig. 6 for the reference scenario. The same spatial pattern is evident in all UKCIP02 scenarios, with the principal difference being the magnitude of change. All areas show a large increase in degree-days, with the smallest increases in western coastal areas and the uplands. By analogue, the projected increases for the Medium-High Emissions scenario in many non-upland areas (~200 degree-days) would imply a climatic shift to conditions currently found in southern England (i.e. >1300 degree-days). Lower increases in the uplands are mainly a reflection of the low temperatures and hence the lower relative values of AT0 degree-days in these areas. Any interpretation of the lower AT0 increases in western coastal areas requires caution, as these outlying areas are actually defined and parameterised as 'sea' on the HadRM3 grid (Fig. 6), producing potentially erroneous anomalies for land sites (Rivington et al. 2008).

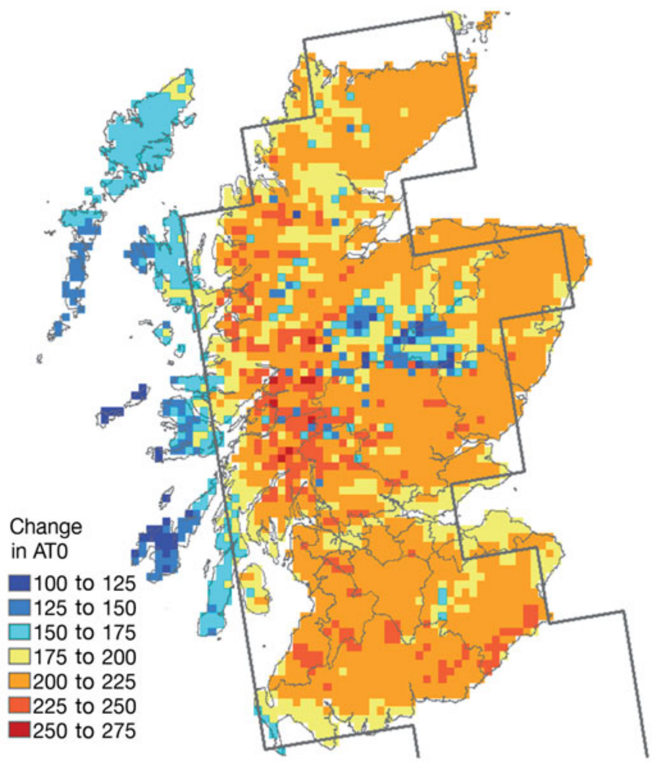

Fig. 6. AT0 change (in degree-days) from 1981–2000 to the 2050s in Scotland for the UKCIP02 Medium-High Emissions scenario. HadRM3 'land' area defined for reference

4.5. Future changes in MPSMD

Fig. 7 shows projected changes in MPSMD for the reference scenario. Again there are significant west–

east differences in Scotland, with potentially large increases in soil moisture deficits in the east and south (50 to 150 mm) contrasting with the lesser changes in the west (<25 mm). As a result, the drier areas in the east are projected to become rather drier while much of the west continues to retain its predominantly wet conditions. This shift is characteristic of all UKCIP02 scenarios, with the increases in ET_0 throughout the country being modified by the projected changes in precipitation patterns, such that the west tends to remain generally wet whereas drier summers become much more common in the east.

The changes in MPSMD also draw attention to anomalous and potentially dramatic changes in ET_0 over eastern uplands compared to the present-day situation. These changes apparently result from large vapour pressure deficits simulated by the HadRM3 climate model during summer months, in conjunction with relatively windy conditions, driving a powerful soil-drying effect. Whether these changes are a model or downscaling anomaly or potentially representative of 'real' change is the subject of further investigation. Other workers using the PM method have noted anomalously high future ET_0 rates, while assessing future water resources, and have discounted these values due to discrepancies with baseline net radiation data in the climate model (Ekström et al. 2007). However, we adjusted HadRM3 net radiation data to be consistent with observations rather than use raw model output. Hence any anomalies are directly attributable to model parameterisation, particularly the accuracy of radiation, soil moisture and evapotranspiration feedbacks, which are a major area of uncertainty in climate models, despite their importance for impact assessments (Cornwell & Harvey 2007). Nevertheless, the implications of such potentially large non-linear changes in soil moisture levels for these upland areas are considerable, not just for water resources but for agriculture, biodiversity and organic soils acting as carbon stores.

4.6. Future changes in LCA 'prime' land

With the sustained rise in temperature predicted by future scenarios, MPSMD therefore becomes the dominant factor influencing spatial variation in the LCA climatic constraints. Fig. 8 shows the resulting distribution of 'prime' land based just on climate constraints for the reference scenario. It is evident that the climatic amelioration removes the LCA climate constraints for much of east and south Scotland, meaning much more land is potentially of 'prime' quality. When

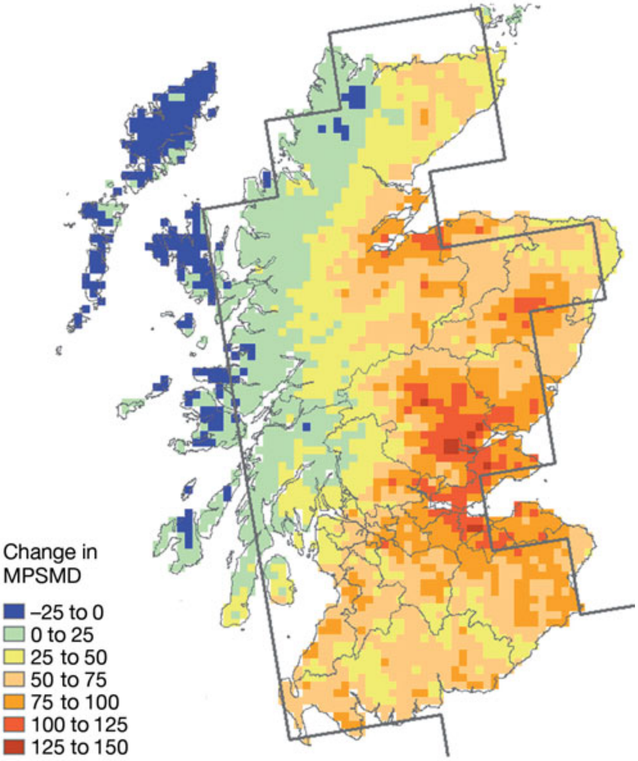

Fig. 7. MPSMD change (in mm) from 1981–2000 to the 2050s (2046–2065) in Scotland for the UKCIP02 Medium-High Emissions scenario. HadRM3 'land' area defined for reference

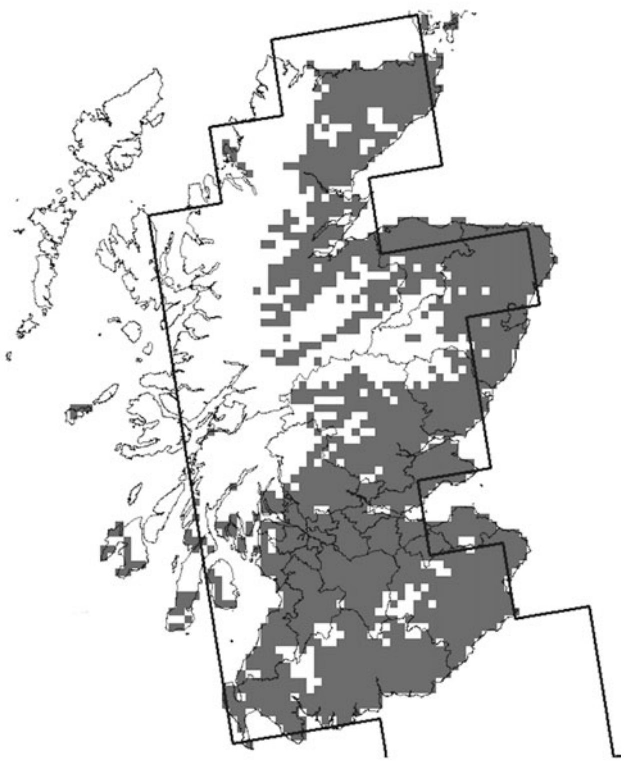

Fig. 8. LCA 'prime' land for the 2050s, solely defined by climatic constraints. UKCIP02 Medium-High Emissions scenario. HadRM3 'land' area defined for reference

the climate data are combined with the soil and topographic constraints, many of these potential areas are excluded due to the intrinsic properties of the land (Fig. 9). However, by comparison to Fig. 5, the combined results still suggest that considerable areas of new 'prime' land could develop under climate change by the 2050s; this is a consistent result across all UKCIP02 scenarios. This implies significant new opportunities for agriculture, particularly in eastern Scotland and in the 'marginal' areas fringing the uplands. By contrast, the scenario analysis implies much of western Scotland exhibits little new 'prime' land potential despite the temperature increases, and this can be attributed to the continuing wet conditions and low MPSMD values, although frequently soil and topographic constraints prevail as well.

5. DISCUSSION

Our scenario-based analysis of future land capability has indicated that climate change is likely to substantially modify the current range of options for land use in Scotland, and evidence from recent change suggests that this may indeed already be occurring. Regionally, land-use options in the east and south of the country are implied to increase, while they remain constrained in most western districts. The potential expansion in areas of 'prime' land would be mainly at the expense of the lower-graded land (Classes 5, 6 and 7).

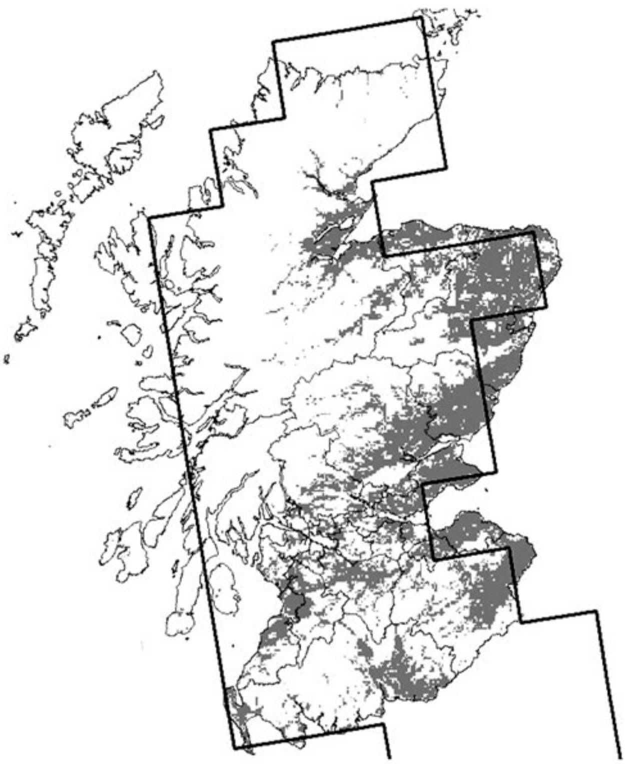

Fig. 9. 'Prime' land in Scotland for the 2050s, adding soil and topographic constraints. UKCIP02 Medium-High Emissions scenario. HadRM3 'land' area defined for reference

As the original LCA system is firmly embedded within land-use planning in Scotland, this has major implications for strategic planning at multiple scales (national, regional and local) because some of these land-use options are not presently being actively considered and deliberated. Furthermore, potential changes in agricultural land classes have implications beyond farming because, if they occur, they will be particularly manifest in more 'marginal' land that currently has other uses such as for woodland, buffering water supplies or maintaining biodiversity. In particular, the projected reductions in Classes 5, 6 and 7 could strongly impact on environmental priorities because these areas have experienced the least disruption from intensive farming and therefore often have a high biodiversity value. Moreover, these areas also often store large amounts of carbon in organic soils that are vulnerable to disturbance (Smith et al. 2007).

Both the agricultural land-use and broader environmental issues strongly imply the need for a revised land capability system in order for it to continue to meet a broad range of stakeholder needs. The 2-parameter LCA climate classification using AT0 and MPSMD is most suitably applied as a screening tool for national or regional-scale land-use assessments, but with the proviso that a more detailed appraisal would probably identify additional constraints. Hence, although the 2-parameter LCA identifies the maximum potential class for an area of land, other factors can be more dominant at the local level, and Bibby et al. (1982) identified a series of other climate-related constraints that can act to reduce the LCA class potential. Most notable of these additional climate factors was wind exposure, especially in coastal areas or due to topographical influence; however, current spatial trends in wind data for the UK have uncertainties relating to inhomogeneous station data (Barnett et al. 2006), and future scenario projections for wind typically have extremely low confidence (Hulme et al. 2002). For a more refined LCA, the interaction between climate and soils is the key influence: further research is addressing this topic, particularly with regard to established indices for soil wetness and susceptibility to drought (Lilly & Matthews 1994). For example, it is conceivable that some areas currently defined as 'prime' land may not maintain that status in the future due to increased soil moisture stress, implying that climate change necessitates a re-examination of the LCA climatic classification in the 'warm, dry' sector of Fig. 1. In Scotland, the supply of irrigation water to counter soil moisture deficits is currently a relatively minor issue, and is used only on a few crops (e.g. potatoes), but the projected changes in MPSMD imply that irrigation may become rather more important in the future. This suggests further refinement of the LCA to identify future areas of 'prime' land dependent or non-dependent on additional irrigation supply, with resultant implications for strategic planning.

It should also be recognised that, although not directly included in the original LCA, year-to-year variation as well as 'average' long-term conditions have an important influence on land-use or productivity (e.g. Semenov & Porter 1995). Hence, an area perceived as having a high interannual variability of land quality may result in some crops being considered too risky, despite their potentially higher value, due to the inherent low predictability of returns. In this context, although Hudson & Birnie (2000) noted that areas of 'prime' land had a tendency to be the least climatically variable, they advocated mapping risk zones of climate variability as an extension of the LCA. By using the GIS climate data from the present study, an initial assessment of this risk can be made with individual years assigned to a notional 'prime' or 'non-prime' class based upon the established LCA thresholds. Aggregating the yearly data for the 1961–1980 and 1981–2000 periods allows an annual likelihood assessment for a 5 km cell attaining 'prime' land status, together with its changing status through recent decades (Fig. 10). This initial analysis implies that the risk of land being 'non-prime' in a particular year has decreased throughout much of eastern Scotland, while it has increased in western Scotland. This has implications for development of the future scenarios, which as defined here presently have unchanged climate variability, and supports further refinement of the LCA system to explicitly include variability.

Other potential refinements to the LCA method also deserve a robust appraisal, with the primary objective being to retain a practical, popular land capability system that communicates genuine agroclimatic constraints on land use. Most notably, several key assumptions require further testing. For instance, the use of median and quartile values that remove the influence of extreme years may be considered less appropriate than using the mean value, as extreme years do undoubtedly have an influence on land-use decisions (Risbey et al. 1999, Smit & Skinner 2002, Reid et al. 2007). A further enhancement could evaluate the influence of a variable or dynamic land cover, rather than a reference surface of grass, with regard to ET_0 and MPSMD values. It may also be pertinent to explore the sensitivity of the LCA to different ET_0 schemes, especially given the anomalous net radiation and ET_0 values derived from climate models (Section 4.2.2). These refinements relate to critical climate–land surface interactions operating through energy balance and

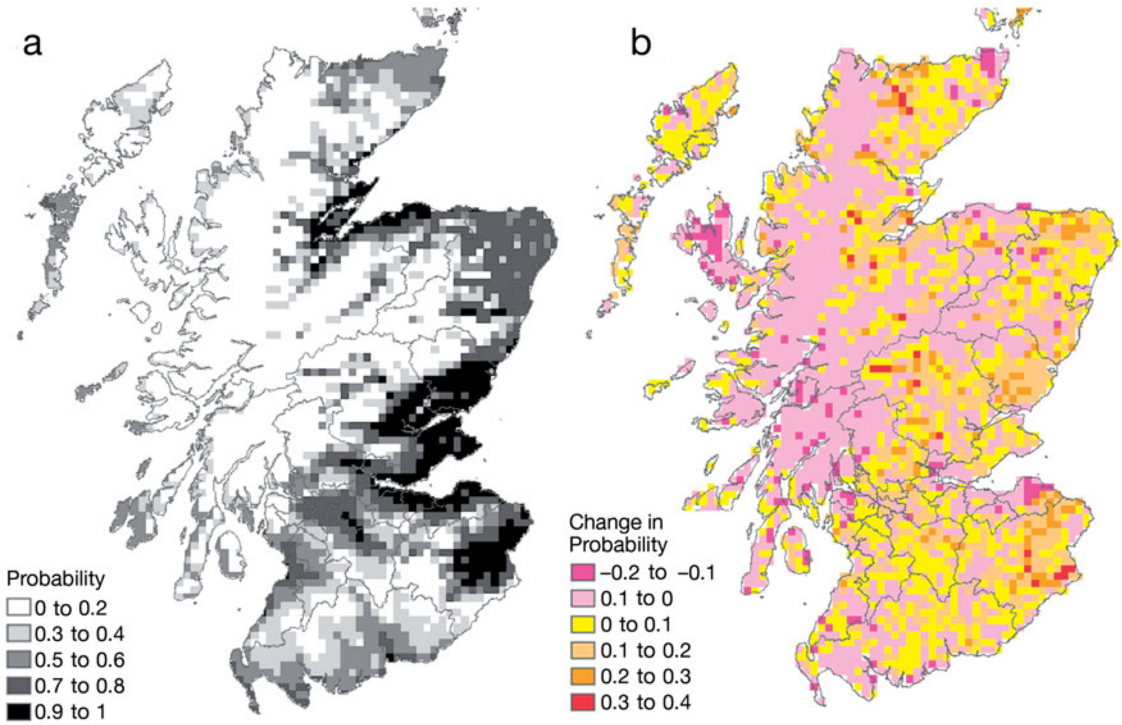

Fig. 10. (a) Annual likelihood of land being 'prime' for 1981–2000 and (b) change in likelihood between 1961–1980 and 1981–2000

water budget feedbacks, which could have profound implications for land use and land management.

With regard to the scenario analysis, we have only used a single climate model (HadRM3). Although principally developed as a general screening tool at this stage, a more robust analysis should include additional climate models and a more advanced downscaling procedure. Systematic biases have been detected in HadRM3 climate parameters such as underestimates of summer precipitation (Blenkinsop & Fowler 2007, Rivington et al. 2008) and overestimates of radiation (Ekström et al. 2007). Although we circumvented these biases by interpolation of the model change fields onto baseline observation data, a range of climate models would allow clearer recognition of key uncertainties in future projections (especially those related to climate–land surface feedbacks). Furthermore, more sophisticated techniques than the Δ method to downscale the model data to the 5 km scale (e.g. Semenov & Brooks 1999, Kilsby et al. 2007), although requiring considerable extra effort, would be potentially able to distinguish changes in local-scale phenomena such as 'rain shadow' effects (e.g. Malby et al. 2007) that may significantly modify land capability at that scale. Alternatively, such information could be derived by local case studies of LCA variability using site-specific downscaling approaches (Rivington et al. 2007).

With regard to confidence in the projected future changes, we can infer a very high confidence that AT0 will increase, although the rate and magnitude are less certain. We can also infer that MPSMD will increase, but with lesser confidence because changes in precipitation are less certain, although most climate models suggest summer drying for the UK and all indicate greater evaporation rates.

A more refined evaluation of future LCA would also require detailed assessments of future soil wetness, soil droughtiness and soil erosion risk. Of these, wetness and droughtiness are likely to be the factors that will be modified most under climate change. As a consequence, some areas may become more favourable for agriculture with, for example, shorter periods at field capacity under moisture retentive soils; by contrast, other areas may become more disadvantaged, for instance with increased drought (and possibly erosion) risk on sandy and gravelly soils. However, these are the product of complex inter-relationships and feedbacks involving climate, soils and often land-management practises, collectively providing a major source of uncertainty.

The current LCA classification for many Scottish soils, particularly those used for arable and improved grassland, is determined by soil wetness and how this affects the workability, trafficability and poaching risk. The LCA system requires soil properties (soil wetness class, depth to an impermeable horizon and the retained water capacity of the surface horizon) to be integrated with climatic wetness data (via field capacity period). Soils with similar properties but in different climatic contexts can therefore have different LCA classifications. This relationship will be modified under climate change scenarios, both spatially and temporally, as the number of days at field capacity changes.

Currently, soil droughtiness does not affect many Scottish soils, although the results from our study suggest that this is likely to alter as the climate changes. Soil droughtiness is assessed in the LCA system by comparing the available water capacity (AWC) in different soils, and at various depths exploited by different crops, to monthly MPSMD data. For future LCA evaluation, this would require cumulative soil moisture deficit curves to be constructed for a series of representative sites, which would then subsequently be adjusted for different crops based on their ground cover at different times of the year.

This application demonstrates the potential for GIS and database routines to provide a fully operational and automated LCA system that can incorporate all regional and local parameters involved in the final classification, including the more complex soil–climate interactions. Compared to the original approach, the speed and flexibility of the new method readily facilitate the incorporation of new data and the evaluation of different scenarios.

6. CONCLUSIONS

By adapting and updating an operational land capability system, valuable insights have been gained into the influence of current and future climate change on land-use potential. The application to Scotland indicates that, particularly in the east of the country, many areas will have greater flexibility of land use. These results suggest that the current LCA working system needs to be revised in order to continue to meet its strategic objectives and to plan for the expected consequences of future climate change. The strong relevance of land capability for planners and managers means that new information can have direct applications, providing an accessible medium through which to translate future climate change projections. Although our study focussed on land capability for agriculture, the findings also have strategic land-use implications for other rural stakeholders, including forestry and nature conservation interests. Land capability can therefore play an important role in raising awareness and in planning anticipatory adaptation responses to climate change. From an international perspective, these findings strongly concur with the perceived need to update FAO guidance on land evaluation to include both ecosystem services and climate change (FAO 2007).

The analysis of land capability change has also demonstrated that in addition to temperature, soil moisture plays a critical role in determining options for land use. However, soil moisture tends to be rather poorly parameterised in climate models, especially with regard to key land-surface feedbacks (Cornwell & Harvey 2007). In some localities, positive feedback during warmer summers may lead to enhanced soil drying due to reduced energy demand for latent heat of vapourisation and consequent increase in sensible heating (e.g. Brabson et al. 2005, Rowell & Jones 2006). This could be further influenced by the reduced uptake of water by plants from enhanced stomatal closure, which would reduce energy transfer through evapotranspiration (Betts et al. 2007). Within current 'cool-wet' bioclimate zones such as Scotland, the potential implications of summer drying would therefore be 'extraordinary', not only for land-use activities, but for related issues such as biodiversity and terrestrial carbon stocks. These implications would vary according to context, but are highly likely to go beyond the current coping range of climate-adaptive measures. Consequently, the role of soil moisture deserves increased emphasis and integration within climate modelling and land-use research.

Acknowledgements. Funding was provided by the Environment—Land Use and Rural Stewardship research programme of the Scottish Government's Rural and Environment Research and Analysis Directorate (RERAD). The UKMO/UKCIP climate datasets were provided under licence by Defra through the UK Climate Impacts Programme. Advice and comments were provided by Prof. S. Albon, Dr. K. Matthews, Dr. C. Campbell and Mr. G. Hudson.

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Editorial responsibility: Mikhail Semenov, Harpenden, Herts, UK

Submitted: February 2, 2008; Accepted: May 7, 2008
Proofs received from author(s): August 6, 2008