CRANFIELD UNIVERSITY

A. PARTL

THE POTENTIAL EFFECTS OF CLIMATE CHANGE ON LAND USE IN THE ENGLISH UPLANDS: A CASE STUDY FROM THE FOREST OF BOWLAND

SCHOOL OF APPLIED SCIENCES
Land Management

MSc THESIS
Academic Year: 2010 - 2011

Supervisor: T. Brewer
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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science

ABSTRACT

The uplands of England are recognized as providing many important economic, social and environmental benefits, such as, an open space for recreation, clean water supply and a large storage of organic carbon in its abundant peat soils. However, various studies predict that growing concerns about food and fuel security together with changing climatic conditions could force the current upland's low intensity and diverse land use towards intensification in unsustainable ways. The study used the FAO Framework for Land Evaluation as a base for producing suitability maps for selected land use/cover types defined according to topography, soil and climate requirements of characteristic crops and/or plants for each land cover type. The suitability maps for the present state were compared with the current land use derived from the Corine Land Cover data, and to those produced for the 2050s, using UKCP09 climatic projections for medium and high emission scenarios. The results generally showed similar patterns in suitability for most of the land cover types. Exceptions were predicted in some areas for agriculture with a minor increase in new potential suitable places, and a decrease in quality of areas suitable for mires. None of the locations in the study area were classified as highly suitable for any of the land cover types assessed. The main limitation of the approach used is the interpretation of the results: the suitability modelling does not exactly describe the future land use, but only provides information about potential suitability for defined purposes.

Keywords:

land suitability, land use, land cover, UKCP09, GIS modelling

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This thesis has been prepared in the format used for scientific papers appearing in the journal *Agriculture, Ecosystems and Environment*. The paper includes an extended literature review.

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The potential effects of climate change on land use in the English uplands: a case study from the Forest of Bowland

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Keywords: land suitability, land use, land cover, UKCP09, GIS modelling

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1 INTRODUCTION

The prediction of future climate and socio-economic changes should lead to better tackling of the environmental challenges in the years to come and wiser management of the world's ecosystems (Dockerty et al., 2005; FAO, 2007; OECD, 2008). Some of the anthropogenic changes which have already been made to ecosystems have clearly improved the way which people live and have helped economic development. However, some of these improvements have been achieved at the increasing cost of degrading many ecosystem services, such as, a decrease in water quality, climate regulation or soil degradation (MEA, 2005).

At a global level, the Millennium Ecosystem Assessment has found that ecosystem services have been altered much more swiftly over the last decades than at any other time in history (MEA, 2005; Verburg et al., 2006). With the human population growing and thus the demand for food, fibre and fuel, it is likely that we will be faced with great challenges in the future (FAO, 2007).

The findings at the UK national level were very similar to those from the global level. In the UK National Ecosystem Assessment, primary drivers have been identified as being responsible for changes in the UK's ecosystems and the services they provide. One of the more significant changes is the conversion of natural habitats and the intensification of their use. This has resulted in a decline of their extent in favour of enclosed farmlands and urban areas (UK NEA, 2011). Threatening the natural areas, that are providing important and demanded services, could be one of the possible reactions to growing demands.

One of these natural habitats are undoubtedly the uplands which are important providers of the UK's biodiversity, carbon sequestration, fresh water supply, natural beauty and many recreational opportunities (CRC, 2010; Reed et al., 2009b,c).

Moreover, uplands are also seen as areas facing upcoming challenges in sustainable production of the previously mentioned benefits and are threatened by a rising concern of food security, which could lead to land use intensification

(CRC, 2009; Reed et al., 2009c; NE, 2010). In this context, almost any single change in variety of land use of these vibrant but fragile areas could be easily one of the main pressures influencing the outcome of the uplands (Audsley et al., 2006).

To illustrate this complex situation, a certain piece of land could be used for energy crop production to reduce greenhouse gas emissions. Alternatively it could be used for forestry to enhance carbon sequestration, or it could have served for agricultural production. This shows that even if the land use will be known, the impacts could be both negative and positive depending upon which ecosystem service was being addressed at that moment (Rounsevell et al., 2006a; Rounsevell and Reay, 2009).

The whole issue becomes more complicated when taking into consideration the effects of climate change which could potentially alter some of the places in an irreversible matter, so that they cannot be used in the same way in future. For example, an increase in temperature may cause the local environmental conditions to become unsuitable for growing certain crops or a decrease in precipitation may change the local environment in such a way that a former habitat can no longer exist (IIASA, 2002).

In order to explore some of these changes, the aims of this study were to propose a likely future land use scenario resulting from 'upland squeeze' after different climate scenarios and to identify the possible implications on ecosystem services, from the predicted land use and possible impacts on society.

To reach these aims, the main objectives were:

1) to select appropriate UKCIP climate and socio-economic scenarios to describe the main drivers influencing future land use

2) to apply selected models to derive upland squeeze outcomes, modelling and presenting those by GIS

3) to evaluate the outcomes of the modelling in comparison with the current conditions.

2 LITERATURE REVIEW

2.1 UK uplands

The definition of uplands varies; elevation, topography, soil type or vegetation are usually the criteria used to define this type of ecosystem. One of the most preferred designations is after the European Commission: Less Favoured Areas (under EC Directive 75/276) (Reed et al., 2009b; Defra, 2011). The LFA classification compromises areas where the productivity of the land is the main limiting factor in achieving a higher profitability in farming. These limitations are due to environmental conditions such as a harsh climate resulting in a short growing season, low natural soil fertility, high altitudes or steep slopes (Reed et al., 2009b).

2.1.1 Upland benefits

Starting with the key facts, UK upland areas cover about 30% of the whole UK; in England they compromise 17% of the land area; they provide home to about 2 million people and are considered to be some of the last remaining natural areas in England (NE, 2001; CRC, 2009; Reed et al., 2009c).

From the ecosystem services perspective, water supply is probably the most important service after agricultural production. Moreover, upland rivers, reservoirs and groundwater maintain water quality, providing 70% of the UK's drinking water (NE, 2010). The peat soils in the UK uplands represent the largest carbon storage with about 300 million tonnes of organic carbon in peatlands (CRC, 2009; DEFRA, 2011). The regulating services provide for the reduction of the natural hazards such as the risk of soil erosion and flooding downstream by providing a large retention capacity (Reed et al., 2009b, NE, 2010). In addition, 75% of the uplands are designated as National Parks or Areas of Outstanding Natural Beauty (AONB), making them valuable areas of landscape and heritage (CRC, 2009). More than 50% of England's Sites of Special Scientific Interest (SSSI) are in the upland areas indicating their clear the importance for upland wildlife (EN, 2001; CRC, 2009). Accounting the cultural services, uplands also create non-material benefits such as a popular place for tourism, creating recreational opportunities with 40 million people visiting England's upland National Parks (CRC, 2009; NE, 2010).

As a result, UK uplands are widely and undoubtedly recognized by researchers, government and non-governmental organisations as unique areas which provide various economic, social and environmental assets. However this understanding is not shared by the vast majority of the people (Reed et al., 2009a,c; UK NEA, 2011). Because of the association with the name of its designation, LFA, they could be seen as areas suffering from severe disadvantages rather than places providing valuable assets. For example the Commission for Rural Communities suggests there must be a principal shift in the way they are treated and perceived (CRC, 2009).

2.1.2 History and future of the uplands

The diverse nature and appearance of UK uplands has resulted from both human activities such as land use, and diverse environmental factors (Holden et al., 2007). Although the uplands have been grazed for thousands of years, they did not always have their current appearance. Native woodland clearance by Mesolithic hunter-gatherers created semi-natural habitats and on-going pedogenesis with climate change gave rise to the spread of blanket peat (Reed et al., 2009b). Medieval times were characterised by sheep farming intensification, followed by forest plantations beginning in the 1920s, and more recently with a trend towards extensification of production (Reed et al., 2009b,c).

Currently, many studies have found that upland areas are facing challenges and pressures in response to climate change. There is a growing concern about food security with potential changes in land uses. For example, agricultural intensification, both changes in grazing and burning in different areas, is a threat for the present distribution of ecosystem services (URS and Promar, 2008; CRC, 2009; NE, 2009; Reed et al., 2009a,b,c; NE, 2010; DEFRA, 2011).

The changes might not always be seen as something negative, because some potential transitions in one area may have important opportunities for another area (Rounsevell et al., 2006b). For example the recent DEFRA (2011) policy review identified that it would financially support characteristic upland hill farming as a one of the ways of promoting the green economy and as a way to demonstrate how to successfully achieve sustainable food production.

2.2 The climate change scenarios

Climate change could be defined in two ways. Firstly, as basically any change in the nature of the climate, which can be observed by fluctuations of its properties, and which lasts more than a few or several years, normally longer than decades. And secondly, narrowly the term climate change describes only changes in climate associated with anthropogenic activity, both direct and indirect, that modifies the state of the climate besides its natural variability (IPCC, 2007).

Climate scenarios are appropriate tools for climate change analysis, usually describing the potential behaviour of climate variables after different greenhouse gas emissions, which are believed to be the most important drivers of climate change (Nakicenovic et al., 2000; Audsley et al., 2006).

Specific scenarios for the UK are available from the UK Climate Impacts Programme. For example UKCP09 is a probabilistic projection providing more complex information based on results from 10,000 model simulations for 3 different emission scenarios (Jenkins et al., 2009; Clark et al., 2010). However, the confidence level of the projections for different variables is not the same, for example there is much more confidence in the projections of mean temperature than those of mean precipitation (Jenkins et al., 2009).

There are no special climate scenarios for British uplands. So, the upland areas are predicted to undergo the similar climate changes as any other place in the UK. According to the central estimate, mean temperature is going to increase depending on location from 2.5 to 4.2 °C. Precipitation is going to increase in winter up to +33%. But in the summer, precipitation is predicted to decrease to about -40% in some parts of England. On the other hand, changes close to zero are predicted for some parts of Scotland for the same season (Jenkins et al., 2009).

2.3 Land evaluation and suitability classification

It's been a long time since the first internationally known and published study about land evaluation, the 'FAO Framework for Land Evaluation', was published, but the main aims and principles are still the same. Although the decisions on land use have long since been part of the human society, it can be argued that people or mainly individuals taking these decisions, learned from the past (FAO, 1976). Land evaluation helps in an ideal case of land use planning to find the most sustainable use of land resources with respect to different climatic parameters, topography and soil, because every piece of land has its own biophysical limitations (IIASA, 2002; Malczewski, 2006). The final land use setting comprises of social and economic conditions in certain area as well (FAO, 1976; Davidson, 1992).

The classification itself is based on assessment of the land into standard land suitability classes which are defined for chosen land uses (Dent and Young, 1981). As indicated previously, the increasing population with increasing demand for food is a driving force of intensification to obtain the most from the land. On the other hand, this claim of a new land for agriculture could cause a larger risk of inappropriate land use. This could result in a loss of production potential or it could cause an irreversible damage to natural resources in the worst case (IIASA, 2002; MEA, 2005). Interestingly the idea of sustainability is not a product of the recent decade as might be seen from various ecosystem assessments, but it is grounded even in the original land suitability classification (FAO, 1984; Dent and Young, 1981; Davidson, 1992).

Nevertheless Dent and Young (1981) states that it was originally designed for planning of individual farms, the evidence from subsequent years showing its application in both developing countries and developed countries at a wider scale (Sys, 1991; Audsley et al., 2006). Many studies also documented a use of such suitability assessments for both individual crops and certain land use classes (e.g. Bydekerke et al., 1998; Cools et al., 2003; Zomer et al., 2008). The importance of an evaluation methodology for rural planners was also outlined by Kalogirou (2002) and Rounsevell et al. (2003), emphasizing the use of GIS in managing the spatial data and visualising the results. Apart from employment in agriculture, the land suitability studies were proven to be very relevant also for certain valuable nature habitats in their suitability modelling for maintaining the biodiversity in relation with climate change (Dockerty et al., 2003; Holden et al., 2007; Trivedi et al., 2008).

These and many other examples demonstrated the importance of land evaluation and suitability, not only as an aid in spatial planning, but also in the case of climate change and changing demands for ecosystem services. GIS could be the strong tool in analysing and identifying the problematic steps in land use planning and management (Bush, 2006; Malczewski, 2006).

2.4 The study area - The Forest of Bowland

As a representative area of the uplands of England, the Forest of Bowland was selected. The study area is located in the north-west of England, covering about 1,115 square kilometres of rural land, with about 803 square kilometres designated as an Area of Outstanding Natural Beauty (AONB). In terms of landscape units the Joint Character Areas consists of the Bowland Fells, Bowland Fridge and Pendle Hill (Fielding and Haworth, 1999).

The Bowland Fells are primary occupied by open blanket bog and heather moorland, with some areas converted to moorland upland pasture, mainly covered by low-productive grassland (Fig. 1). The Bowlands Fells upland core is surrounded by the intermediary landscapes of Bowland Fridge and Pendle Hill consisting of woodland areas and undulating pasture (FB, 2009).

Additionally, the Bowland Fells contain areas designated as Special Areas of Conservation (SAC), Special Protected Areas (SPA) and Sites of Special Scientific Interest (SSSI). The whole area has a great value from a conservation point of view.

3 MATERIALS AND METHODS

3.1 Data: topography, soil, climate scenarios, land cover

For the analysis of the topography, a digital elevation model was obtained from Ordnance Survey/Edina Digimap Collections. Considering the resolution of the rest of the data used in the study, OS Land-Form PANORAMA DTM (1:50000) was chosen instead of the Profile dataset. DTM data had 50m horizontal grid interval, 1m height resolution and 5m height accuracy (http://edina.ac.uk/digimap).

Soil data was obtained from LandIS at the National Soil Resources Institute and in particular the following datasets (vector data, 1:250000) were used in this study: the NATMAP vector, NATMAP associations, SOILSERIES and HORIZON (http://www.landis.org.uk).

There are three UKCP09 emission scenarios (low, medium, high) available from UK Climate Impact Programme. Climate data projected for medium and high emission scenarios for the 2050s were used mainly in order to model the two worst case situations (http://www.ukcip.org.uk/ukcp09). The 2050s were selected from various climate scenarios because, the impacts of climate changes will be more obvious in this time period. On the other hand, the 2050s are not so far off, which enables the potential impacts of such changes to be felt even by the current generation.

The UKCP09 scenarios were derived from the Hadley Centre Global Climate Model for three different emission profiles: low, medium and high greenhouse gas emissions (Jenkins et al., 2009). The data used in this study was for the medium and high emissions scenarios projected at 90% probability; for annual average precipitation (mm) from which a yearly sum was calculated and monthly temperature averages for a growing season from April to September (°C).

The information about current land cover was derived from Corine Land Cover dataset from 2000 mainly for comparison with the suitability maps for the present state (Fig. 1).

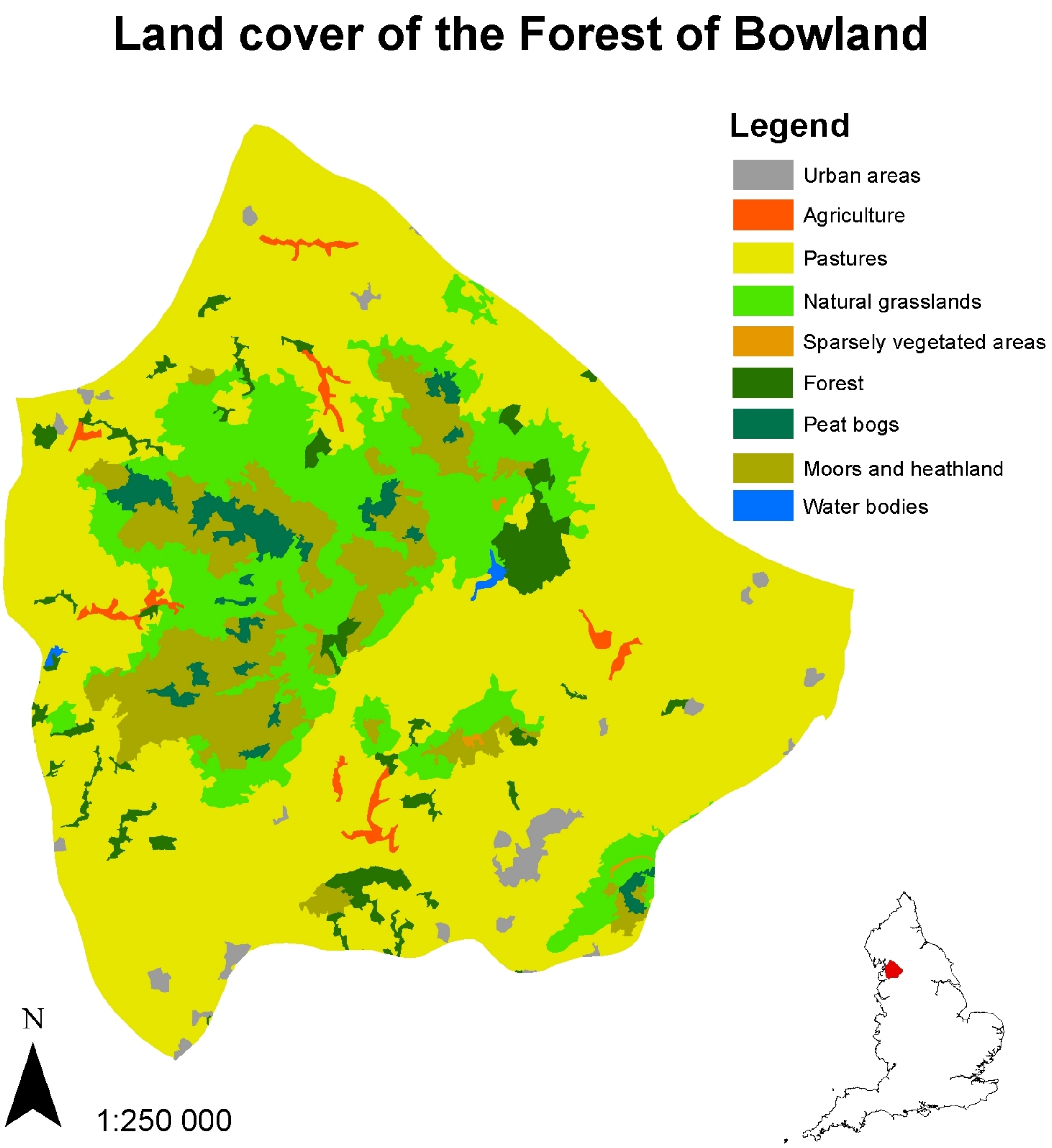

Fig. 1. Overview of the land cover in the study area derived from Corine Land Cover 2000 (The classification of a different land cover types appearing in legend was modified and aggregated in some cases and it is not identical with the original in Corine)

3.2 Land cover classes creation

Four main land cover classes were established in order to investigate the effects of climate change on the suitability of the land in the study area: arable, woodland, moorland and pasture. The arable class was chosen mainly in order to examine a possibility of the shift towards a more intensive management with a provision of food or renewable resources. The woodland class represented potential change of a once naturally abundant habitat in the uplands. The moorland class is defined for two typical natural habitats, which were predicted to be potentially influenced by climate change. In the case of the last class, a variety of possible subclasses were offered, such as an improved grassland, rough grassland, neutral grassland (Morton et al., 2011). But their designation among different land cover products is not uniform, and a definition using the same principles as for other classes would be complicated, because of a large variety of grass species. Thus, a rather general one was established using only *Lolium perenne* species.

The overall summary of each land use/cover class with the subclasses and environmental variables for suitability classification is provided in Appendix A (Table A.1). A brief description and further justification of each (sub) class is provided below along with the cited literature used for creating classes.

Although requirements of the species were taken mainly from the UN ECOCROP database, where the value ranges are given for optimal and absolute conditions, sometimes the values were not consistent with the data from other sources. Thus, when it was possible, the information from ECOCROP provided a base, with the optimum range compromising the highly suitable rank (S1) and absolute values forming a range for a marginally (S3) respective not suitable rank (NS). However, the values were slightly adjusted after a critical comparison with sources about distinct upland habitats. Then, the moderately suitable rank (S2) was proportionally calculated.

3.2.1 Arable

The arable class represented the most intensive use of the land with mainly provisioning ecosystems services. Selected crops were wheat (*Triticum aestivum*), potato (*Solanum tuberosum*), maize (*Zea mays*) and oilseed rape (*Brassica napus ssp. oleifera*). This class currently covered very little of the area, mainly because of limiting conditions preventing more intensive management. So, this was analysed to see, if the potential climate changes could promote a further propagation of arable crops.

All of these crops could be grown for biofuel and bioenergy, representing not only the potential for a food production, but also a source of the renewable resources (Tuck et al., 2006). The requirements and classification were taken mainly from the UN ECOCROP database and other studies published (FAO, 1983; IIASA, 2002; Kalogirou, 2002; Tuck et al., 2006; URS and Promar, 2008; Bellarby et al., 2010).

3.2.2 Woodland

The woodland class with a wide range of regulating, cultural and provisioning services represented the case as to how climate change could influence the areas already naturally forested and the potential creation of suitable places for new plantations. In the natural landscape and ideally during artificial plantations, forests are rarely monocultural, a slightly different approach was chosen for this class. The National Vegetation Classification (NVC) was used to define two subclasses, with a pair of typical and dominant tree species characteristically occurring in uplands. Then, the suitability ranges were taken from a combination of the requirements for growing conditions of the both species. The woodland NVC W11 was deputized with sessile oak (*Quercus petraea*) and downy birch (*Betula pubescens*), and W9 with common ash (*Fraxinus excelsior*) and European rowan (*Sorbus aucuparia*) (FAO, 1984; Sys et al., 1991; Hall, 1997; Fielding and Haworth, 1999; Hill et al., 1999; EN, 2001; Hall et al., 2004; Musil and Mollerova, 2005).

3.2.3 Moorland

One of the most intensively studied upland natural habitats - heathland - with a narrow ecological valency, managed by burning and grazing was defined using the NVC class upland heathland, typically dominated by common heather (*Calluna vulgaris*) and common bilberry (*Vaccinium myrtillus*) (Fielding and Haworth, 1999; Hill et al., 1999; EN, 2001; Holden et al., 2007; Jones et al., 2007, MFP, 2009).

Because of the undoubted importance of peatland in carbon sequestration, a second subclass was defined by peat moss (*Sphagnum spp.*), usually accompanied by cottongrass (*Eriphorum vaginatum*) (Fielding and Haworth, 1999; Hill et al., 1999; EN, 2001; Holden et al., 2007; Jones et al., 2007).

3.2.4 Pasture

Currently the most prevailing land use/cover in the study area was defined for the modelling after Perennial ryegrass (*Lolium perenne*), which is grown in general for grazing. Requirements were taken from the UN ECOCROP database and literature (FAO, 1991; IIASA, 2002).

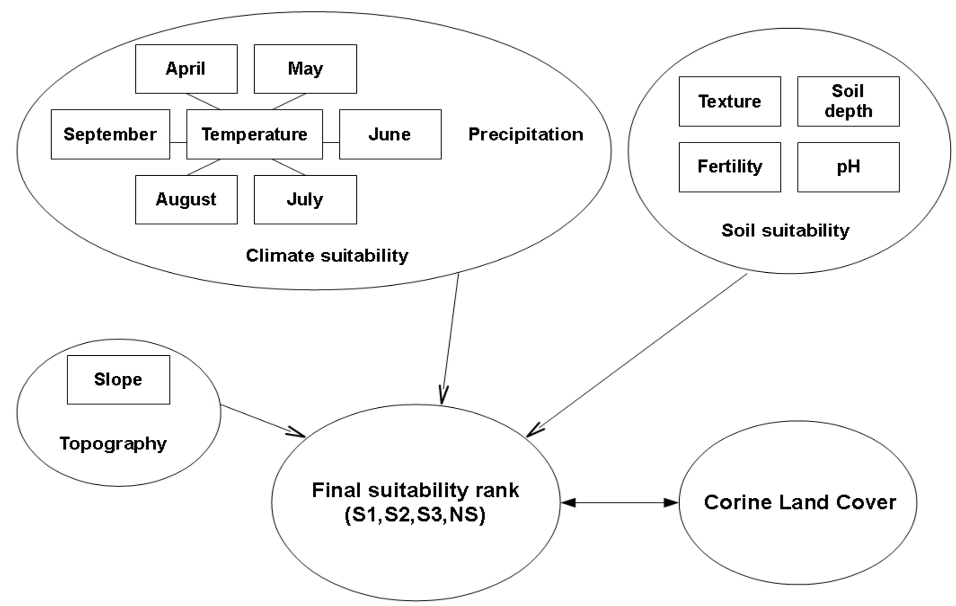

Fig. 2. Flowchart of the analysis used in the study.

3.3 Land suitability classification: analysis

Every location in the given study area was classified for all land use/cover classes, when the topography, climate and soil conditions were assessed first individually and then among themselves (Fig. 2). If a site was assigned as not suitable for one requirement (soil depth, pH,etc.), then the same site received the rank of 'not suitable' as the final one. If the location was ranked as suitable (S1-S3), the final suitability class was calculated as an average from those previously used for testing.

The whole analysis was carried out and suitability maps were produced with the tools in the ArcGIS software package. The summary of the different suitability classes used, with corresponding description is provided in Table 1.

Table 1. Description of suitability ranks used in suitability analysis (adopted from Dent and Young, 1981).

Class		Description
S1	Highly suitable	Land having few or no limitations to sustainable use under defined purpose (possible minor reduction of productivity)
S2	Moderately suitable	Land having moderate limitations for sustainable use (the limitations will reduce the productivity and/or increase required inputs)
S3	Marginally suitable	Land having severe limitations for sustainable use under defined purpose (required inputs can be only marginally justified)
NS	Not suitable	Land having severe limitations to sustainable use under defined purpose and excluding any possible way of overcoming the limitations

4 RESULTS

4.1 The present suitability

The suitability maps created under the present climatic conditions were compared with the current land use derived from Corine Land Cover data. It is important to remember, the land cover classes defined in this study and used for the suitability modelling could not represent all of the land cover type defined in Corine. This is because, even if all the classes were used they do not comprise all of the arable crops grown in the area. A summary of the land area for each class and scenario is provided in Appendix B (Table 1).

4.2 Arable

The outcomes from the modelling for the arable land cover shown new potentially suitable places for agriculture crops in the study area, both for the present state and for the 2050s (Figs. 3-5).

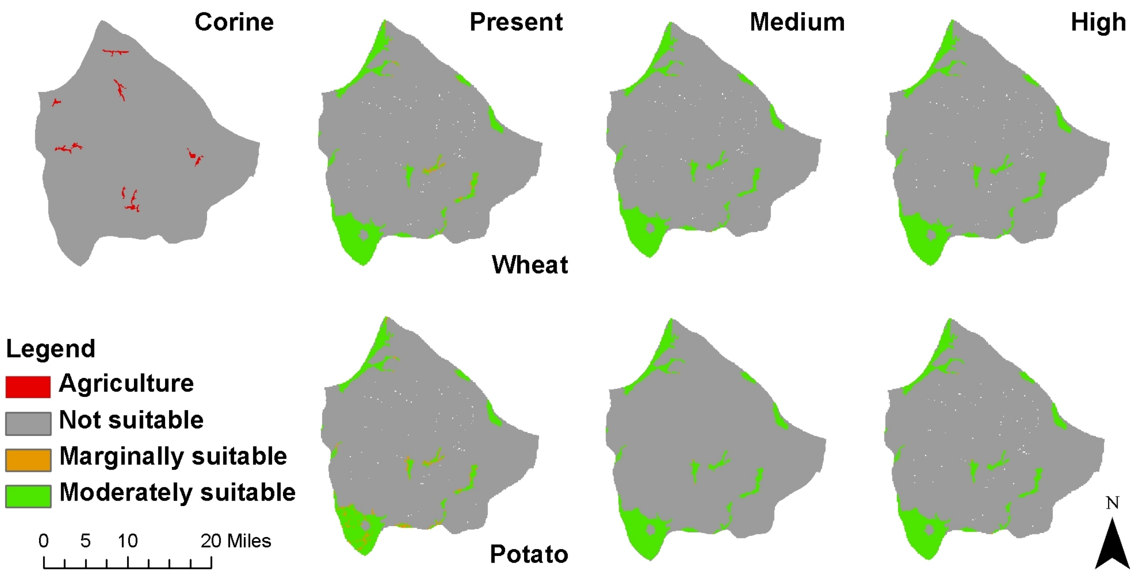

Fig. 3. Comparison of the present agriculture land cover derived from Corine Land Cover data and suitability maps for wheat and potato under the present state, medium and high UKCP09 emission scenarios for 2050s.

However, considering the present baseline suitability, there was only small difference (6.9 km^2) in the extent of the new areas for growing wheat and potato. Only minor increase in the suitability rank was observed for a small area for potatoes, from marginal to moderate suitability. Although, there was also only a small area in the north-western part of the study potentially suitable for growing maize, the total area was increased for 2050s on the similar level of suitability as for wheat and potato. This shift was due to a rise of temperature under the both emission scenarios. It also caused an improvement in rank quality from marginal to moderate suitability for growing oilseed rape in two areas located near north-eastern border of the study site.

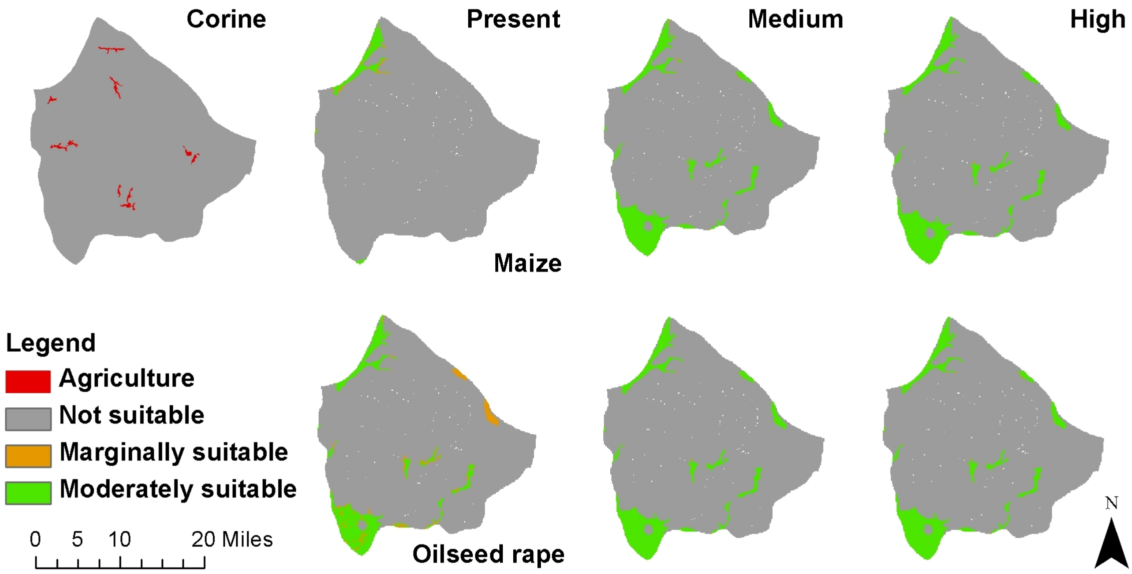

Fig. 4. Comparison of the present agriculture land cover derived from Corine Land Cover data and suitability maps for maize and oilseed rape under the present state, medium and high UKCP09 emission scenarios for 2050s.

The present suitability maps show that the extent of arable crops is driven and limited mainly by soil fertility. When the suitable climatic conditions are present, the final suitability for all arable crops is very similar under medium and high UKCP09 emission scenarios for 2050s.

However the present suitability maps did not show any match with the agriculture land cover class derived from Corine.

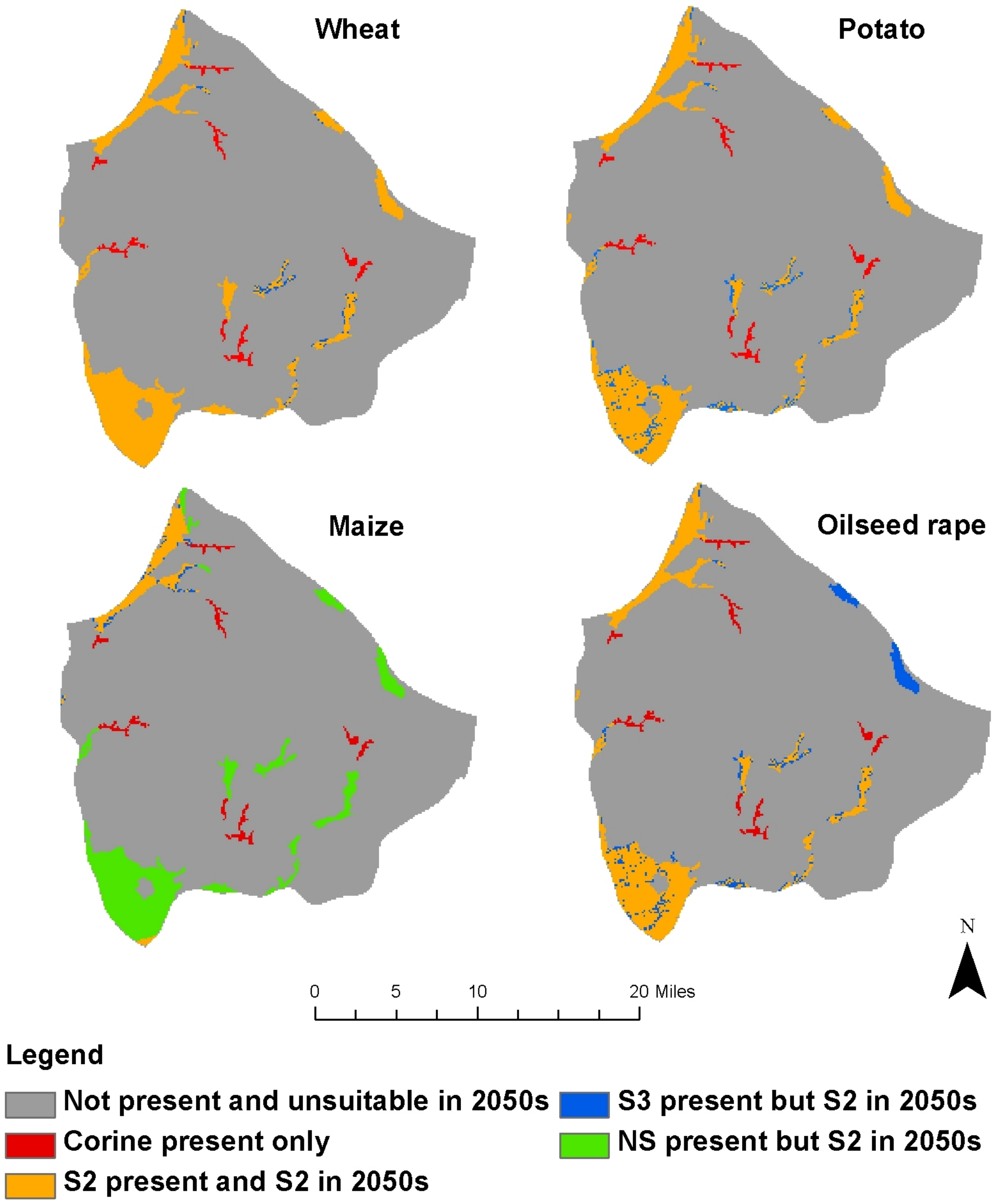

Fig. 5. Changes in individual areas for arable in suitability classes under present state and UKCP09 high emission scenario in 2050s compared with actual land cover in Corine.

4.3 Woodland

The current distribution of deciduous forest in the study area was very low, especially in comparison with the modelled suitability under all scenarios

(Fig. 6-7). The north-eastern part of the study area was even classified as unsuitable under present conditions for *Quercus petraea* and *Betula pubescens* woodland (W11) because of temperature requirements.

This was caused by gridded temperature values, where the current value for the north-eastern area was peculiarly the lowest (5.6 °C), in comparison with the north-western area, where the gridded value was the highest (7.4 °C) for the whole study area in April.

The suitability maps showed a large amount of suitable sites for new forests. But fewer sites were predicted to be suitable for *Fraxinus excelsior* and *Sorbus aucuparia* woodland (W9). The extent of the suitable areas were determined mainly by pH, soil texture and soil depth according to the suitability model. The suitability maps show the high similarity under both emission scenarios and also in comparison with maps for present state, suggesting that, the forest cover is pretty resilient to climate change in the Forest of Bowland.

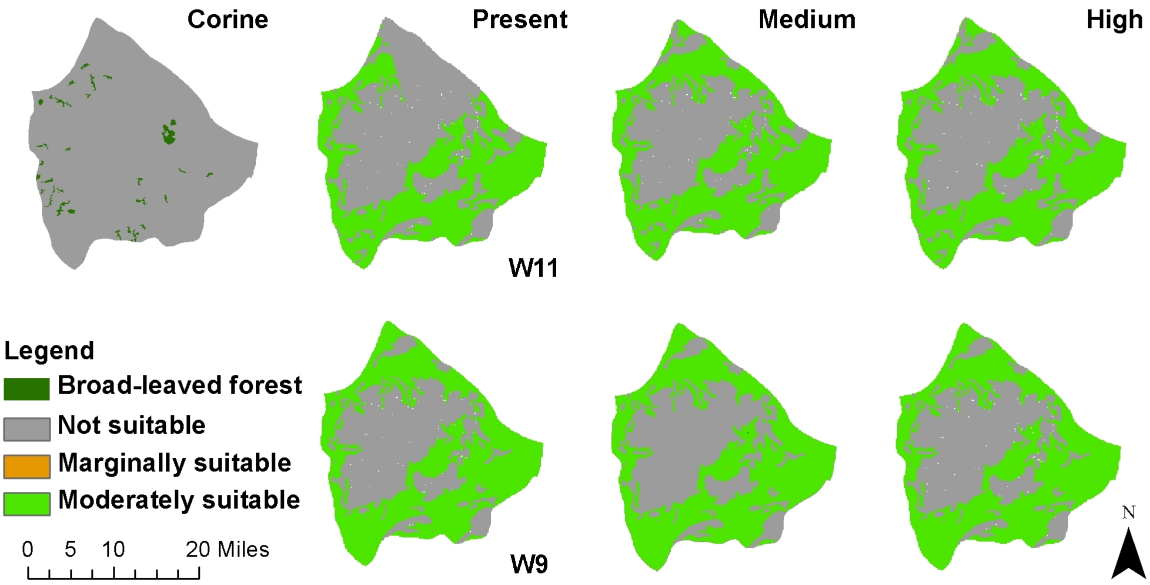

Fig. 6. Comparison of the present broad-leaved forest land cover derived from Corine Land Cover data and suitability maps for W11 and W9 woodland under the present state, medium and high UKCP09 emission scenarios for 2050s.

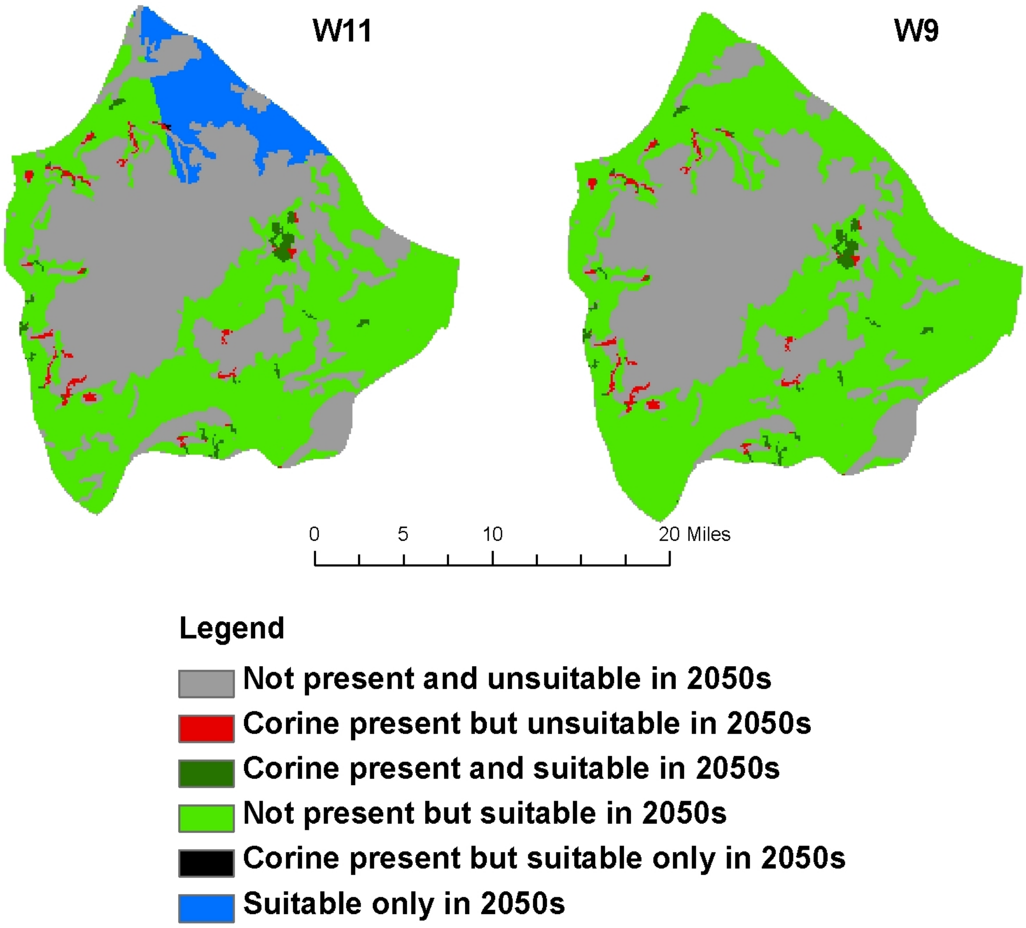

Fig. 7. Changes in individual areas for woodland in suitability classes under present state and UKCP09 high emission scenario in 2050s compared with actual land cover in Corine.

4.4 Moorland

The areas found to be moderately suitable for heathland (*Calluna vulgaris and Vaccinium myrtillus*) corresponded with the current distribution of heathland derived from Corine, even with a much larger extent of potentially suitable areas (Fig. 8). Additionally, similar sites were assessed as moderately suitable under the current state and under both emission scenarios. The comparison with Corine land cover predicted a potentially larger distribution of heathland than it is at present (Fig. 9). No impact of the predicted climate change was observed.

However, the situation with mires (*Sphagnum spp.* and *Eriophorum vaginatum*) was slightly different, the worst suitability rank was achieved by some sites that were previously moderately suitable under medium and high emission scenarios (Fig. 8 and 10). This was caused by a predicted temperature increase in the 2050s. Although minor, this was the first observed evidence in the study so far, where the changing climatic conditions negatively influenced a future distribution of a land cover type.

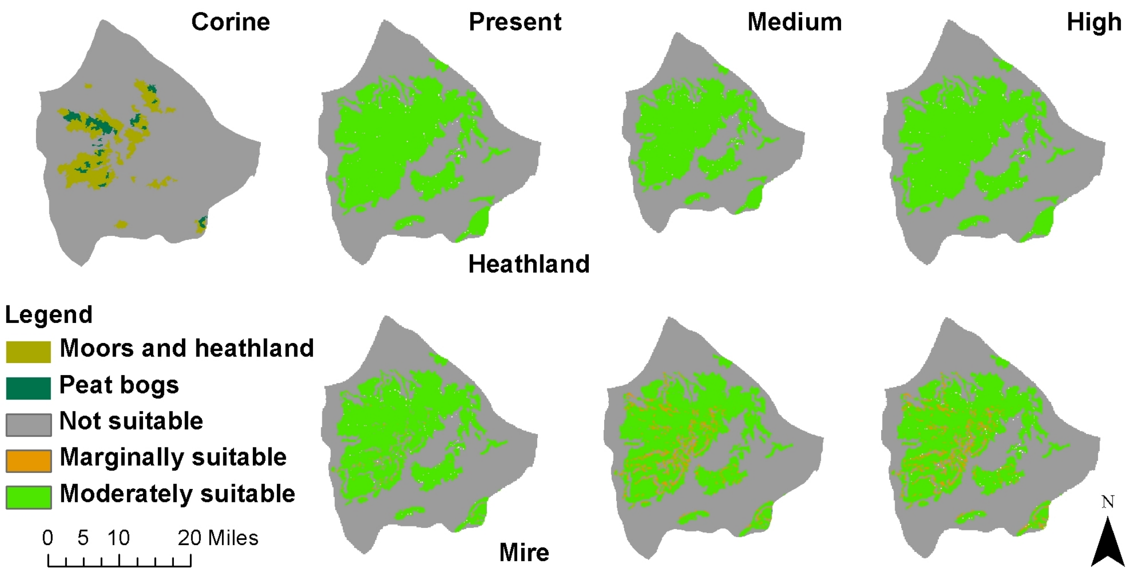

Fig. 8. Comparison of the present peat bog, moor and heathland land cover derived from Corine Land Cover data and suitability maps for heathland and mire under the present state, medium and high UKCP09 emission scenarios for 2050s.

The modelled suitability for moorland land cover was primary determined by the peaty soils for both land cover types preventing any further expansion to sites where there were not present.

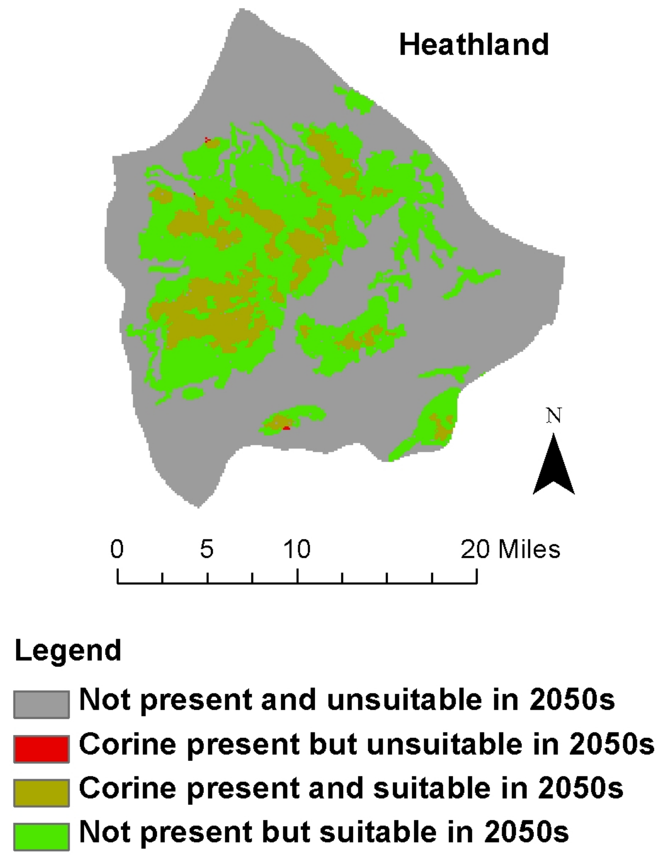

Fig. 9. Changes in individual areas for heathland in suitability classes under present state and UKCP09 high emission scenario in 2050s compared with actual land cover in Corine.

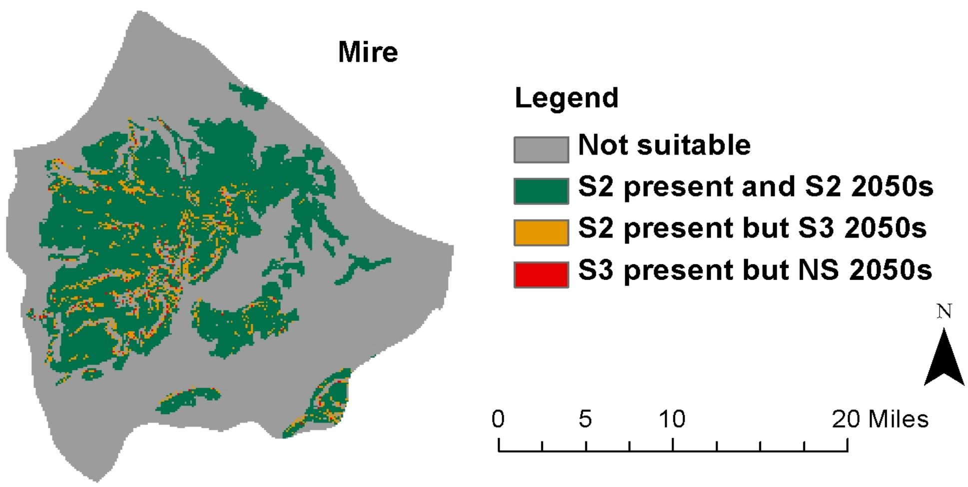

Fig. 10. Changes in individual areas for mire in suitability classes under present state and UKCP09 high emission scenario in 2050s compared with actual land cover in Corine.

4.5 Pasture

Pasture (*Lolium perenne*) was currently the most abundant land cover type in the study area and the present suitability extent was similar to that predicted by the suitability analysis (Figs. 11-12). Generally, the analysis assessed previously unsuitable sites for moorland land cover as moderately suitable for pasture and vice versa. This stratification was caused by the peaty soil texture again. Primarily, pH was affecting the potential distribution with a minor influence by soil depth and fertility.

However, the Corine land cover showed pastures present even in sites assessed as unsuitable by the analysis. It was observed, that the precipitation slightly negatively and temperature slightly positively influenced the future possible distribution of the pasture land cover. There was no difference between individual emission scenarios.

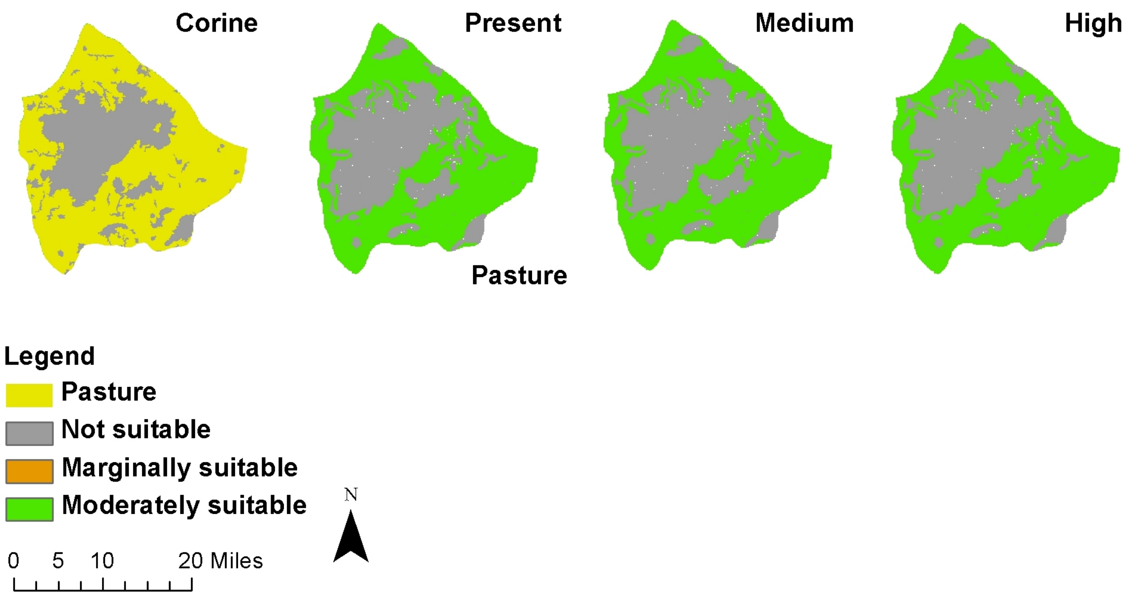

Fig. 11. Comparison of the present agriculture land cover derived from Corine Land Cover data and suitability maps for pasture under the present state, medium and high UKCP09 emission scenarios for 2050s.

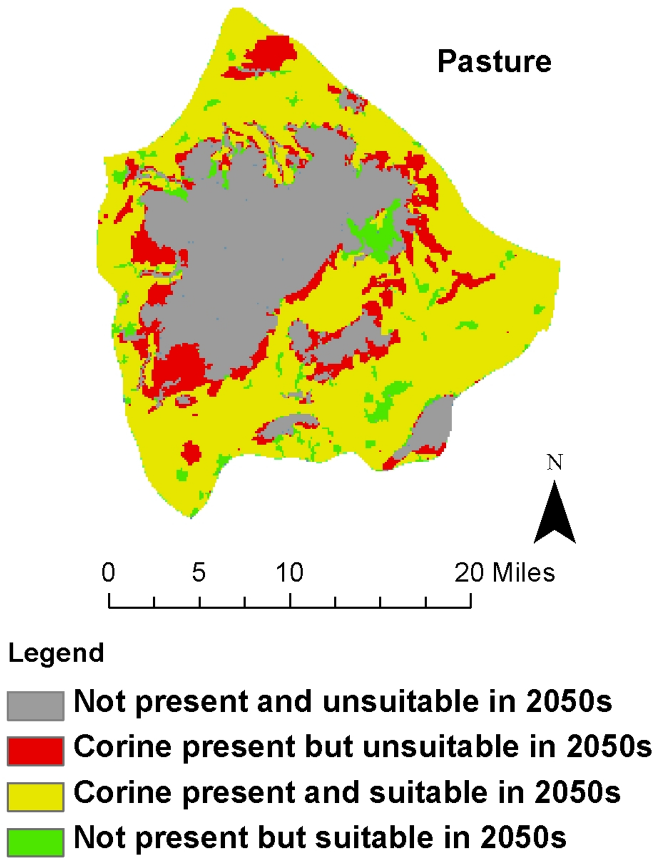

Fig. 12. Changes in individual areas for pasture in suitability classes under present state and UKCP09 high emission scenario in 2050s compared with actual land cover in Corine.

Table 2. Cross tabulation of areas (km^2) of land cover classes and suitability rating for present and the 2050s medium and high emission scenarios.

	Scenario	Not suitable	S3	S2	S1
Wheat	Baseline (present)	1012.3	3.4	99.3	0
	2050s (medium)	1012.1	0.3	102.6	0
	2050s (high)	1012.1	0.3	102.6	0
Potato	Baseline (present)	1012.4	10.2	92.4	0
	2050s (medium)	1012.1	0.3	102.6	0
	2050s (high)	1012.1	0.3	102.6	0
Maize	Baseline (present)	1095.5	2.6	19.9	0
	2050s (medium)	1012.1	0.3	102.6	0
	2050s (high)	1012.1	0.3	102.6	0
Oilseed rape	Baseline (present)	1012.4	18.2	84.4	0
	2050s (medium)	1012.1	0.4	102.5	0
	2050s (high)	1012.1	0.4	102.5	0
W11	Baseline (present)	612.2	0.04	502.8	0
	2050s (medium)	527.6	0.04	587.4	0
	2050s (high)	527.6	0.04	587.4	0
W9	Baseline (present)	496.9	0.06	618	0
	2050s (medium)	496.9	0.06	618	0
	2050s (high)	496.9	0.06	618	0
Heather	Baseline (present)	670	0	445	0
	2050s (medium)	670	0	445	0
	2050s (high)	670	0	445	0
Mire	Baseline (present)	695.3	4.3	415.4	0
	2050s (medium)	697.2	38.1	379.7	0
	2050s (high)	697.3	39.2	378.5	0
Pasture	Baseline (present)	473.4	0	641.6	0
	2050s (medium)	473.4	0	641.6	0
	2050s (high)	473.4	0	641.6	0

5 DISCUSSION

5.1 Limitation of suitability maps

One of the limitations of the suitability maps is that they do not exactly provide information, as to how the land use/cover would look like, they only provide information about how suitable a certain area is for a certain purpose. Even if a large part of the study area would be classified as a suitable for agriculture, it does not necessarily mean that it would be used for agriculture.

The final decision about the arable land is taken by farmers, who generally want to maximize their profit from their land, within the context of financial stimulus, grants, support payments and limitations, which will influence their decisions in certain directions (Rounsevell et al., 2003). But no matter the financial payments, the main physical constraints are still the same - the soil and climate (Audsley et al., 2006). Producing the suitability maps could certainly help to identify these constraints, because they are also able to provide the location of land potential.

5.2 Limitations of probabilistic projections

Jenkins et al. (2009), stated that outcomes from the probabilistic projections are not giving simple answers, rather providing a range of possible values accompanied with a probability, which cannot be interpreted as an absolute value. Instead of that, the Cumulative Distribution Function is used, describing a climate change value of probability being less than or greater than a certain value. For example, a 50% probability threshold would be a median, also called a central estimate. The probability level used in this study were the 90% threshold. It is characteristic in terms of changing climatic conditions as the worst case scenario with the highest change. Thus, the correct interpretation would be, the scenario which is very unlikely to be exceeded.

5.3 Difference between Corine and present suitability

In a few cases, the land cover derived from Corine dataset shown some sites with a certain land cover type present, even on sites, which were assessed as unsuitable for that land cover. This suggests basically two possible answers, an error in suitability classification or in the Corine land cover. It is probably the case that the absolute data ranges defined as requirements are not accurate in modelling the transition zones from one environmental feature to another. For example, a soil texture rather than changing as a discrete quantity, transforming immediately from a loamy texture to a sandy texture at one point, is a continuous quantity, resulting in a gradient. This is the primary reason suggested for the observed difference between predicted areas for pasture and pasture from Corine.

In the case of agriculture, the land cover was taken from Corine cover type 'Land principally occupied by agriculture, with significant areas of natural vegetation', which may not seem appropriate for comparison for purely agriculture areas. It was done mainly because it was the only agricultural land cover type convenient for comparison at present in the study site, in order to have at least a land cover type to compare with.

Additionally, more differences could caused by the fact that the requirements for land cover classes were designed in order to represent the land cover type as it is characteristic in uplands. For example, *Betula pubescens* could grow in larger areas than is evident from Table A.1. The narrower definition of the suitable area was used because, *B. pubescens* appears in uplands in combination with *Quercus petraea*, thus the final designation was limited.

5.4 Interpretation of suitability maps

In terms of creating potentially suitable places for a new land cover type, the suitability analysis showed almost no new suitable sites for arable crops, except for maize, bringing its possible extent to a similar level as other crops modelled by the study (Table 2). Although, it might seem sometimes that climate change will alter the environmental conditions, enabling new crops to grow, this trend was not proven under medium, nor high emission scenarios for the 2050s. The state where the soil conditions are limiting arable distribution will not be overridden by the changing climatic conditions.

Modelling outcomes for the woodland land cover pointed into the past, when the uplands were originally forested, proposing the largest possible chance in land cover/use change (Reed et al., 2009b,c). However, the majority of the places, which were assessed as moderately suitable for woodlands, are currently occupied by pastures for hill farming, meaning that, the change from the model of providing current profits to a model of providing profits in much longer period would be required. For forestry this is undoubtedly the case, so the shift seems rather unlikely to happen for economic reasons, because the forest plantations are not harvested by the generation who planted it but at least by the next generation (Audsley et al., 2006).

Suitability maps also show much larger areas of possible distribution of moorland than are actually present. Also there was a decrease in suitability class for some sites under changing climatic conditions. There could also be another limitation other than environmental conditions limiting the extent of this natural habitat, explained by the theory of ecological niches. The environmental variables which were used in the modelling comprise only the fundamental niche, describing the range of conditions where a plant in this case could exist. However, the realized niche is also a result of the interactions with the other organisms usually forcing themselves into a much narrower space, creating the additional limiting factor for a wider spread for now and in the future (Hutchinson, 1957).

The evidence of this fact could be for example *Calluna vulgaris*, a species being able to occupy a wide range of habitats, but being prevented from growing in all of them by other flora species. Moreover, the extent of *C. vulgaris* is also determined by its management through periodical grazing and burning (Fielding and Haworth, 1999).

5.5 Factors determining the suitability and climate change impacts

The results from the suitability analysis proposed that the upland areas were shown to be resilient to the changing climatic conditions, except for the mire land cover. Such a state was aimed at by NE (2010) to be achieved in relation of climate change.

In the rest of the cases, it was altitude and peaty soils limiting the suitability, because where they were present, only the moorland land cover was classified as a suitable for these areas. This result suggests that the carbon storage in peaty soils is safe from the anticipated threat of land use intensification (e.g. NE, 2009; CRC, 2010).

On the other hand, the lower situated locations without peaty soils showed the highest flexibility overall for the different land cover types. The majority of the sites were currently covered by pastures, so if there will be any land cover or land use change, it is very likely that it will be at the expense of pastures.

Finally, it was primary the soil conditions limiting the suitability for the land cover types used in this study. The impacts resulting from climate change in the 2050s have been shown to have a small impact on suitability, making a contrast with a large change predicted by Bush (2006).

5.6 The UK uplands future scenarios

Reed et al. (2009b) provided a comprehensive set of scenarios indicating several possible options of the upland future, where the first set of scenarios were characterised by an intensification of land use in upland areas. Volatile food prices, global and national food shortages could lead to agriculture intensification and expansion of arable crops into upland valleys, and because the modelled suitability did not provide sufficient convenient space for this expansion, the likelihood of this scenario is very low. That is in contrast with an predicted large expansion of energy crops into upland areas (Bellarby et al., 2010).

It is much more likely that the land use change would be in favour of new forest cover comparing the predicted agriculture and woodland suitability. Although, the forests offer an another way of sequestering the atmospheric carbon, the afforestations of peaty soils are highly controversial, excluding sustainable wood production (FC, 2000).

Another proposed future scenario is the withdrawal of agricultural management and re-wilding (Reed et al., 2009b). Abandoning some of the areas covered by pasture could cause a further propagation of heathland into lower altitudes and a large increase in the extent of forest and shrub habitats. The consequences of this shift would cause the loss of agriculture areas followed by more socio-economic disadvantages in upland communities. Fortunately, it is not likely to be the case, because even DEFRA (2011) has proposed a plan which promises financial support for hill farmers.

5.7 Implications on ecosystem services

Although, one of the aims of the study was to predict possible implications on ecosystem services, it is very difficult to conclude something with high certainty. The suitability maps indicated a few directions of possible development in land use change, but even their combination with uplands future scenarios proposed by Reed et al. (2009c) did not provide a single answer.

Nevertheless, several predictions of such impacts could be stated when applying a simple framework of ecosystems services covered in NE (2010). From provisioning services, there is a chance of increasing the food production from farming, because new fields for arable crops could be established. On the other hand, the suitable areas for these crops are actually mainly covered by pasture (for hill farming) creating the opportunity for the modification of the current composition of food sources.

The carbon storage in peaty soils, probably the most important benefit of English uplands from regulating services, would most likely remain unthreatened as long as it stays unsuitable for more intensive land management. For example, none of the suitable sites for agriculture were predicted in higher altitudes, where these habitats naturally occur. Minor changes in suitability were predicted for mire, though they are mainly located in areas where this habitat is not currently present. The other regulating services such as a flood regulation and provision of clean water could be degraded probably only by unwise land management during the spreading new arable crops into new areas. Further enlargement of a wood cover could in contrast greatly improve the retention capacity by afforesting abundant pastures.

The distinguished appearance of the Forest of Bowland's landscapes created a place of a national significance and provides many cultural services (FB, 2009). There are possible minor changes in the way the cultural services are delivered, but it is very unlikely, that there is going to be a change with substantial impact.

The recent DEFRA (2011) 'Uplands policy review' with CRC (2010) suggested that there should be a public payment for public goods, ecosystem services in this case. This measure is likely to reward land managers for maintaining the quality of ecosystems services from the English uplands and could bring even more positive implications on the benefits provided by uplands.

The presented alternatives might be further improved by using quantitative economic models as suggested by Britz et al. (2010) and Claessens et al. (2009). His study encouraged the application of these models and approaches along with models addressing primary land management. Furthermore, this should bring a more integrated understanding of land use changes.

6 CONCLUSIONS

The suitability modelling showed the main limitations in the interpretation of the maps, because they do not exactly provide information about the future land use/cover. Moreover, many sites were predicted to have high potential for a different land cover types, enabling their further extension and suggesting enough suitable areas for a change in land use. This was predicted both for the present suitability and for the future suitability in 2050s mainly for natural land cover types such as a woodland and moorland.

Generally, there was no major difference between the suitability maps predicted under the different emission scenarios for the same land cover type. Moreover, the upland area came out from the analysis quite resilient to the climatic changes, because even the suitability maps for the present state were very similar to those under future emission scenarios. This applies with an exception for a mire land cover type, which was predicted to have fewer suitable sites in the 2050s.

Finally, the future land use/cover in the 2050s under both emission scenarios will be driven much more by socio-economic changes, rather than climate, as it was also documented by Rounsevell et al. (2006a) and URS and Promar (2008). Moreover, this was achieved in 'the worst scenario'. Even the projected climatic change does not seem to have enough power at 90% probability level to override the prevailing unsuitable environmental conditions for more intensive land management.

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APPENDICES

Appendix A Land cover classes

Table A.1. Summary of the land cover classes with data ranges for each suitability class used in the analysis.

			Suitability class	Topography	Climate	
				Slope (%)	Temperature (ºC)	Precipitation (mm/year)
Arable	Wheat	*Triticum aestivum*	S1	0-3	15-23	750-900
			S2	3-12	10-15; 23-25	525-750; 900-1250
			S3	12-18	5-10; 25-27	300-525; 1250-1600
			NS	>18	<5; >27	0-300; >1600
	Potato	*Solanum tuberosum*	S1	0-3	15-25	500-800
			S2	3-12	11-15; 25-27.5	375-500; 800-1400
			S3	12-18	7-11; 27.5-30	250-375; 1400-2000
			NS	>18	<7; >30	0-250; >2000
	Maize	*Zea mays*	S1	0-3	18-33	600-1200
			S2	3-12	14-18; 33-40	500-600;1200-1500
			S3	12-18	10-14; 40-47	400-500; 1500-1800
			NS	>18	<10; >47	0-400; >1800
	Oilseed rape	*Brassica napus*	S1	0-3	15-25	500-1000
			S2	3-12	10-15; 25-33	450-500; 1000-1900
			S3	12-18	5-10; 33-41	400-450; 1900-2800
			NS	>18	<5; >41	0-400; >2800

			Suitability class	Topography	Climate	
				Slope (%)	Temperature (ºC)	Precipitation (mm/year)
Woodland	Sessile oak & Downy birch	*Quercus petraea & Betula pubescens*	S1	0-16	10-18	1200-1400
			S2	16-25	8-10; 18-22	1000-1200; 1400-1600
			S3	25-30	6-8; 22-26	900-1000; 1600-1700
			NS	>30	<6; >26	0-900; >1700
	Common ash & European rowan	*Fraxinus excelsior & Sorbus aucuparia*	S1	0-16	8-20	500-800
			S2	16-25	6-8; 20-27	450-500; 800-1200
			S3	25-30	5-6; 27-33	400-450; 1200-1700
			NS	>30	<5; >33	0-400; >1700
Moorland	Common heather & Common bilberry	*Calluna vulgaris & Vaccinuim myrtillus*	S1	0-25	8-17	800-1200
			S2	25-60	6-8; 17-21	700-800; 1200-1900
			S3	60-100	5-6; 21-25	500-700; 1900-3200
			NS	>100	<5; >25	0-500; >3200
	Peat moss & Cottongrass	*Sphagnum spp. & Eriphorum vaginatum*	S1	0-25	7-13	1200-1600
			S2	25-60	5-7;13-17	900-1200; 1600-1900
			S3	60-100	3-5;17-21	700-900; 1900-2100
			NS	>100	<3;>21	0-700; >2100
Pasture	Perennial ryegrass	*Lolium perenne*	S1	0-16	14-25	900-1500
			S2	16-30	9-14; 25-30	700-900; 1500-1750
			S3	30-35	4-9; 30-35	500-700; 1750-2300
			NS	>35	<4; >35	0-500; >2300

			Suitability class	Soil			
				Texture	Soil depth (cm)	Fertility	pH
Arable	Wheat	*Triticum aestivum*	S1	medium, organic	50-150	high	6-7
			S2		>150	moderate	5.5-6.7; 7-7.75
			S3				5-5.5; 7.75-8.5
			NS	light, heavy	0-50	low	0-5; 8.5-14
	Potato	*Solanum tuberosum*	S1	medium, organic	50-150	high	5-6.2
			S2		>150	moderate	4.6-5; 6.2-7.35
			S3				4-4.6; 7.35-8.5
			NS	light, heavy	0-50	low	0-4; 8.5-14
	Maize	*Zea mays*	S1	medium, organic	50-150	high	5-7
			S2		>150	moderate	4.75-5; 7-7.75
			S3				4.5-4.75; 7.75-8.5
			NS	light, heavy	0-50	low	0-4; 8.5-14
	Oilseed rape	*Brassica napus*	S1	medium, organic	50-150	high	6.5-7.6
			S2		>150	moderate	6-6.5; 7.6-7.8
			S3				5.5-6; 7.8-8
			NS	light, heavy	0-50	low	0-5.5; 8-14

			Suitability class	Soil			
				Texture	Soil depth (cm)	Fertility	pH
Woodland	Sessile oak & Downy birch (W11)	*Quercus petraea & Betula pubescens*	S1	medium	50-150	high	5-6.2
			S2		>150	moderate	4.3-5;6.2-6.9
			S3	light		low	4-4.3;6.9-7.3
			NS	heavy	0-50		0-4;7.3-14
	Common ash & European rowan (W9)	*Fraxinus excelsior & Sorbus aucuparia*	S1	medium	50-150	high	6.7-7.3
			S2		>150	moderate	5.9-6.7;7.3-7.5
			S3	light		low	5-5.9;7.5-7.9
			NS	heavy	0-50		0-5;7.9-14
Moorland	Common heather & Common bilberry	*Calluna vulgaris & Vaccinuim myrtillus*	S1	peaty	50-150	low	4.8-6
			S2		0-50		4.5-4.8;6-6.3
			S3		>150		3.9-4.5;6.3-6.6
			NS	other		moderate, high	0-3.9;6.6-14
	Peat moss & Cottongrass	*Sphagnum spp. & Eriphorum vaginatum*	S1	peaty	not strictly sensitive	low	3.5-4.4
			S2				3.1-3.4;4.4-4.6
			S3				2.9-3.1;6-4.8
			NS	other		moderate, high	0-2.9;4.8-14
Pasture	Perennial ryegrass	*Lolium perenne*	S1	heavy, medium	50-150	high	5-7
			S2		>150	moderate	4.7-5;7-7.7
			S3		0-50	low	4.5-4.7;7.7-8.1
			NS	light			0-4.5;8.1-8.4

Appendix B Summary of the land area

Table B.1. Total land area (km^2) of the individual land cover classes under baseline, UKCP09 medium and high emission scenarios for 2050s and actual land area for present derived from Corine Land Cover.

		Suitability class	Present area	Baseline area	Medium area	High area
Agriculture			10.91			
Arable	Wheat	S2		99.3	102.6	102.6
		S3		3.4	0.3	0.3
	Potato	S2		92.4	102.6	102.6
		S3		10.2	0.3	0.3
	Maize	S2		19.9	102.6	102.6
		S3		2.6	0.3	0.3
	Oilseed rape	S2		84.4	102.5	102.5
		S3		18.2	0.4	0.4
Deciduous forest			23.86			
Woodland	W11	S2		502.8	587.4	587.4
		S3		0.04	0.04	0.04
	W9	S2		618	618	618
		S3		0.06	0.06	0.06
Heathland			114.23			
Peat bogs			23.84			
Moorland	Heather	S2		445	445	445
	Mire	S2		415.4	379.7	378.5
		S3		4.3	38.1	39.2
Pasture			727.10			
Pasture	Ryegrass	S2		641.6	641.6	641.6