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Assessing the vulnerability of agricultural land use and species to climate change and the role of policy in facilitating adaptation

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ABSTRACT

The term vulnerability has been used in a variety of contexts, including climate change impact assessment. In this paper those issues relevant to climate change impacts on agriculture and species are discussed. Outputs from models are used to assess the vulnerability of farmers and species to climate and socio-economic change by estimating their sensitivity and capacity to adapt to external factors as a means of identifying what causes the differences in their vulnerability.

The results showed that the vulnerability of both farmers and species is dependent on the scenario under consideration. In agriculture, it is the socio-economic scenarios that particularly lead to different patterns of intensification, extensification and abandonment. For species, vulnerability is more related to the climate change scenarios. In both cases, the adaptation options and potential were associated with the different socio-economic futures and policy intervention. The conceptual linking of the two sectors shows that impacts in the agriculture sector and consequent adaptation could have a significant effect on the adaptation potential of species. This demonstrates the importance of cross-sectoral assessments of vulnerability and highlights the importance of sectoral integration in policy development and implementation.

1. Introduction

The term vulnerability is used loosely in many different contexts, from medicine to the poverty and development literature. In global environmental change studies, the concept of vulnerability is often derived from the social sciences (Chambers, 1989; Liverman, 1992; Watts and Bohle, 1993; Blaikie et al., 1994; Cutter, 1996; Woodward et al., 1998). In hazard research, Chambers (1989) introduced the concept that vulnerability has an internal and external dimension and these relate to the capacity to anticipate, cope, or recover from the impacts of a hazard, and to the exposure to risks of the hazard, respectively.

Kasperson (2001) also recognised that interactions exist between the internal capacity of humans to withstand or respond to a risk and the external dimension (risk). Similar interactions occur between the social and economic vulnerability of populations and the degree of resilience of ecological systems. He suggested, therefore, that an integrated approach to both human and natural systems is

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needed if significant progress is to be made in understanding the different vulnerability of regions, places and people. A widely accepted methodological framework to analyse vulnerability arising from these two concepts of the internal and external dimensions (and their interplay) remains to be fully developed.

These ideas relating to exposure and capacity have been incorporated into more recent definitions of vulnerability, especially those relating to climate change. The United Nations Environment Programme provides various definitions of vulnerability that focus on human welfare. For example:

> ''Degree of loss resulting from a potentially damaging phenomenon.'' ''[Vulnerability] is an aggregate measure of human welfare that integrates environmental, social, economic and political exposure to a range of harmful perturbations'' (UNEP, 2001).

While vulnerability is defined by the Intergovernmental Panel on Climate Change (2001a) as:

> ''the extent to which a natural or social system is susceptible to sustaining damage from climate change'' and ''the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including variability and extremes. Vulnerability is a function of the character, magnitude and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.''

Both views of vulnerability incorporate the same essential concepts: exposure, sensitivity and adaptation. The main difference is that in the UNEP concept the exposure unit is focused on human welfare, while the IPCC concept places natural systems alongside the social system.

This distinction has important implications for how the vulnerability of species is viewed with respect to the vulnerability of people, in this case farmers. Many social scientists believe that vulnerability is only a human concept (for example, see Acosta-Michlik and Rounsevell, 2000). Counter arguments include the intrinsic value of species and that human vulnerability can be affected by the loss of services that habitats and species provide (Loreau et al., 2001; Turner et al., 2003a). In this paper it is assumed that, because human activities and species are exposed to drivers of change and inherently display both sensitivity and adaptive capacity, they can be considered vulnerable entities in their own right, with important consequences for humans.

This paper uses research from the Assessing Climate Change Effects on Land Use and Ecosystems: from Regional Analysis to the European Scale (ACCELERATES) project to analyse the vulnerability of agricultural land use and species to exposure to climate change. Its aims are two-fold: (i) to compare approaches for assessing vulnerability to climate change for agricultural land use and species and (ii) to examine the role of adaptation and policy in reducing this vulnerability. By adopting this approach two critical questions can be addressed: (a) what determines the relationship between a change (scenario) and its effects? (b) who or what is vulnerable and where are the vulnerable located?

Similar questions are posed by Turner et al. (2003b), who also suggest a vulnerability framework and stress the need to work with multifaceted coupled systems, linking human and biophysical (environmental) conditions. This framework is tested through three case studies, which show the complexity of factors affecting vulnerability and the need to simplify the framework to facilitate practical application (Turner et al., 2003c). The ATEAM project also has developed a methodological framework for combining potential impacts of climate change on ecosystem services and adaptive capacity into measures of vulnerability (Schröter et al., 2005, http://www.pik-potsdam.de/ateam/). This has been applied to the provision of a range of ecosystem services across Europe. Methodological approaches to assess vulnerability (both sensitivity and adaptive capacity) that include cross-sectoral, multi-scale, and multi-stress relationships, therefore, are an emergent area of research.

There have been a number of studies that have examined, either qualitatively or quantitatively, the individual components of vulnerability. For example, the sensitivity of agricultural systems (Alexandrov, 1997; Metzger et al., 2005) or species (Berry et al., 2002; Segurado and Araujo, 2004; Skov and Svenning, 2004; Thuiller, 2004) to climate change have been examined. A few also touch on the need for adaptation (Hareau et al., 1999; Luo and Erda, 1999; Berry et al., 2003; Chipanshi et al., 2003; Metzger et al., 2005) and Adger et al. (2005) have conceptually addressed the effect of scale on adaptation success.

Assessing vulnerability is important as it enables the identification of areas or resources at risk, and the threats posed by the diminution or loss of such resources that could threaten future sustainable development. Adaptation is an integral part of the assessment, as it is a means of managing (and possibly mitigating) projected changes. It is also an important policy response option, as enhancement of adaptive capacity is seen as a necessary condition for reducing vulnerability, especially in the most vulnerable regions, nations and socio-economic sectors (IPCC, 2001a). Research into adaptation can help reduce negative effects by focusing attention on systems where adaptation can buy time or where adaptation offers few possibilities and thus there is a need to switch to alternative systems or invest in protecting existing ones (Yohe, 2000).

The IPCC (2001a) recognises two types of adaptation: autonomous (or spontaneous) adaptation and planned (or societal) adaptation. Autonomous adaptation occurs at the level of individuals, both human and species. In ACCELERATES, for example, the decision processes of farmers are modelled explicitly and their choices in terms of land use change reflect an autonomous adaptation strategy (Audsley et al., 2006). For species, a change in the distribution of an organism based on its capacity to disperse within a landscape also represents autonomous adaptation.

Planned adaptation refers to the intervention of society through policy. For example, the Common Agricultural Policy (CAP) has traditionally protected farmer incomes, and conservation policy seeks to minimise deleterious effects on species. Within ACCELERATES, autonomous adaptation is a direct output of the project models, whereas planned

Table 1 – Interpretation of the agricultural land use indicators in terms of farmer sensitivity

Indicator	Increases	Decreases
Intensive agricultural area	Results from higher profits for farmers and a more economically viable agricultural system (*low sensitivity*)	Represents a loss of profitability, and consequent moves to more extensive land uses, implying a reduction in the number of farms and farmers (*high sensitivity*)
Extensive agricultural area	Either beneficial or detrimental to farmers, depending on whether previously intensive or abandoned land becomes extensive. If the land was previously intensive, the loss of profit would also imply a reduction in the number of farms and farmers (*high sensitivity*). If the land was previously abandoned, increasing profitability would increase farming (*low sensitivity*)	Either beneficial or detrimental to farmers, depending on whether the land becomes more intensive or abandoned. Intensification is beneficial to farmers because of higher profits (*low sensitivity*). Abandonment is detrimental to farmers, as farming can no longer continue (*high sensitivity*)
Abandoned agricultural land	Results from a loss of profit to the extent that farming can no longer continue (*high sensitivity*)	Represents an increase in profitability and a move to either intensive or extensive land use, implying an increase in the number of farms and farmers (*low sensitivity*)

adaptation is interpreted qualitatively between the different scenarios. Table 1 summarises and compares these two approaches to vulnerability assessment for agriculture and is discussed in more detail in the methodology.

Already much is being done or is proposed to integrate these two sectors (Drucker and Damarad, 2000), as well as re-evaluating their policy relationship (Rogers, 2004) and two examples will be considered here. In 2003, Europe's environment ministers agreed to identify all high nature value farmland areas and take appropriate conservation measures. A report by the European Environment Agency (2004) showed that these areas cover about 15–25% of the European countryside and suffer from land abandonment and intensification. The "second pillar" of CAP reform provides support for less-favoured areas (LFA) and agri-environment schemes. Many LFA overlap with these high nature value farmland areas, but the report still concludes that current policy measures appear insufficient to prevent further biodiversity decline.

The EC-Agricultural Action Plan on Biodiversity is part of the European Community's Biodiversity Strategy, which was developed to fulfil its commitments under the Convention on Biological Diversity (CBD). This seeks to integrate agriculture and biodiversity through such objectives as: the conservation and sustainable use of agro-ecosystems and their interface with other ecosystems, the promotion of farming methods enhancing biodiversity, by linking agricultural support to environmental conditions where appropriate and the development of agri-environment measures to optimise benefits on biodiversity (Hoffmann, 2000). Further integration should be achieved through the EU Sustainable Development Strategy that aims to protect and restore habitats and natural systems and halt the loss of biodiversity by 2010.

This paper uses results of the sensitivity of agricultural land use (Audsley et al., 2006) and species (Harrison et al., 2006) to the exposure of climate change. It then examines an approach to integrating vulnerability assessments for a human (agricultural land use) and environmental (species) sector and links this with possible policy responses.

2. Methodology

2.1. Overview

Vulnerability indicators were devised for agriculture and ecosystems to ascertain the sensitivity of the affected parties (farmers and species, respectively) to climate and socio-economic change scenarios and to assess the role of adaptation. In the case of agriculture, the sensitivity indicators were based on the mapped distributions of changes in agricultural land use (abandoned land, extensive land and intensive land) arising from changes in profitability (Audsley et al., 2006). For species, the indicators were based on changes in suitable climate space (Harrison et al., 2006). Both were generated on a $10'$ latitude $\times$ $10'$ longitude grid for Europe using baseline climate data from New et al. (2001), soils data from the IGBP-DIS Global Soil Data Task (2000), and land cover data from Pelcom (Mücher et al., 2000). The land use model outputs were then aggregated to NUTS2 administrative regions. This was done in order to be able to compare easily the vulnerability between European regions. Although aggregation results in the loss of information, it can be difficult to interpret and visualise the $10' \times 10'$ resolution maps in terms of general trends in vulnerability.

The European climate change scenarios at a $10'$ latitude $\times$ $10'$ longitude resolution were derived from the ATEAM project (Mitchell et al., 2004), and are described in more detail in Harrison et al. (2006) and Rounsevell et al. (this volume). Five scenarios based on two global climate models (HadCM3 and PCM) and four SRES emissions scenarios (A1FI, A2, B1 and B2; Nakićenović et al., 2000) were used: HadCM3 for the A1FI, A2, B1 and B2 emissions scenarios and PCM for the A2 emissions scenario. These were applied for three timeslices (2020, 2050 and 2080). The sensitivity indicators were calculated for each of these scenarios and timeslices. These two climate models were chosen as they show very different projections of future temperature and precipitation across Europe: PCM is relatively cooler and wetter than HadCM3, which is quite a warm and dry scenario for Europe compared with others reported in the IPCC Third Assessment Report (2001b).

Four economic scenarios described by Abildtrup et al. (this volume) were used in the analysis: world markets (WM), regional enterprise (RE), global sustainability (GS) and local stewardship (LS), which are associated with the A1FI, A2, B1 and B2 SRES emission scenarios, respectively. The association of the socio-economic and climate change scenarios is based on internally consistent assumptions about the effects of socio-economic development pathways on global greenhouse gas emissions and thus, climate change. The socio-economic scenarios were based on quantification of narrative storylines that described four alternative societal futures. The A scenarios reflect economically orientated worlds as opposed to the B scenarios that have environmental and equitable policy goals. The scenarios labelled 1 have a globalised focus in terms of international trade and/or cooperation, whereas the two scenarios are focused on regional (and local) issues.

2.2. *Agricultural vulnerability*

As agriculture is a socio-economic system, a vulnerability assessment should address the vulnerability of people within this system (either as individuals, or more conveniently as communities of individuals grouped together as a function of their common attributes and/or objectives). For agro-ecosystems, two generic groups who are potentially vulnerable to environmental change can be identified: (a) *suppliers* (notably farmers, but also retailers and people involved in ancillary agro-industries) and (b) *consumers* of either agricultural goods (food and fibre) and/or agricultural services (landscape and environmental externalities). However, this is a very generic classification. If we examine one group of suppliers, e.g. farmers, it becomes clear that there are many different types of farmers: large farmers, small farmers, dairy farmers, cereal farmers, etc., characterised by their different business activities and socio-economic attributes.

The presence of two potentially vulnerable groups also demonstrates the problem of conflict when assessing vulnerability in human systems in a generic way. For example, the current trend throughout Europe is for large farms to grow at the expense of small farms, through aggregation into larger business units. For example, between 1995 and 2000 the number of farm holdings in the EU15 of less than 50 ha decreased in number by 5.8%, whereas the number of holdings greater than 50 ha increased by 2.2% (European Union, 2004). The smaller farms are more vulnerable to change than larger farms because larger farms benefit from economies of scale. Small farmers certainly benefit from financial support within the current CAP mechanisms, yet their vulnerability has not been resolved and such farms continue to go out of business. Because larger farms are more efficient (due to economies of scale) they produce goods at a lower price for the consumer. Thus, in simple economic terms, the consumer benefits from the vulnerability of the small farmer because if small farmers are more vulnerable their chances increase of being converted to larger farms. What is good for the consumer (lower food prices) is bad for the (small) farmer and vice versa and so, the vulnerability of small farmers is underpinned by a conflict of interest with consumers.

No attempt has been made, therefore, to combine the vulnerability of suppliers and consumers into a single index for agriculture. Instead, this study has focused solely on the assessment of the vulnerability of farmers. European consumers (as a group) are not considered to be vulnerable. In general, they benefit from high incomes of which food consumption represents a relatively small part. All of the future socio-economic scenarios also assume further increases in relative wealth for Europe.

The agricultural vulnerability indicators were derived from the ACCELERATES land use model (see Audsley et al., 2006). The land use model combines two submodels (ROIMPEL and SFARMOD) that simulate crop growth and farm level decision processes. ROIMPEL is based on soil and climate variables, which are used to derive output variables such as nitrogen-limited crop yields, sowing and maturity days and the number of workable days. These are used as inputs to a whole farm model (SFARMOD) (see Annetts and Audsley, 2002; Rounsevell et al., 2003), which also uses details of husbandry provided by a farm database and future economics provided by a scenario database (Audsley et al., 2006). The model assumes that farmers seek to maximise their long-term profits, within the constraints of their situation, taking account of uncertainty in prices and yields (Annetts and Audsley, 2002) and that land use at a regional scale is the sum of decision making at the farm scale (Rounsevell et al., 2003). Therefore, it is assumed that if the land is sufficiently profitable it will be used for intensive agriculture, but land that is marginally profitable is used for extensive agriculture. Land that is not profitable for any agricultural use is classified as abandoned, although such land could be used for other purposes, such as forestry. Both submodels are described in more detail elsewhere (Audsley et al., 2006).

Changes in the areas of intensive, extensive and abandoned agricultural land between each scenario and the baseline were used as generic indicators in the assessment of the sensitivity of farmers. The rules for the conversion of these area changes into farmer sensitivity are given in Table 1. Maps of the indicators allow potentially sensitive regions to be identified. Such area changes are useful indicators of sensitivity because they were derived from a calculation of farmer profit and represent the autonomous adaptation strategies of farmers. Planned adaptation was interpreted in qualitative terms within the constraints assumed by each of the future socio-economic scenarios. This means, for example, that policy plays a reduced role in the A1FI scenario (which is market orientated) compared with a B2 world, which is highly interventionist. The assessment of planned adaptation was based, therefore, on an interpretation of the socio-economic and policy development pathways that underpin each scenario. This approach is consistent with the scenario concept and avoids the need to construct quantitative adaptive capacity indices that can in practice be difficult to validate. The overall assessment of the vulnerability of farmers was based on the combination of the quantitative sensitivity indicators and the qualitative scenario interpretations. Although the interpretation of the indicators discussed in Table 1 affects farmers only, it is important to note that benefits for farmers do not necessarily benefit the wider environment. Intensification, for example, may have negative effects on biodiversity. Conversely, extensification may have positive effects on biodiversity and minimise environmental pollution.

2.3. *Species vulnerability*

In the context of species, it is the species themselves and the habitats they comprise that are vulnerable, although humans may be affected by alterations in the provision of ecosystem services (Parmesan and Galbraith, 2004; Millennium Ecosystem Assessment, 2005). It has, however, been widely recognised that species that are potentially vulnerable include those that have restricted geographical range, small populations, limited possibilities to adjust or occur at high altitude or latitude (Huntley et al., 1997; IPCC, 2001a; Berry, 2004). Little work has been undertaken on providing a quantitative index for assessing the vulnerability of species to climate change. Only Matsui et al. (2004) calculated a sensitivity index based on the difference in the simulated probability of occurrence of *Fagus crenata* between current and future climate scenarios and a vulnerability index as the reciprocal of its probability of occurrence in each grid square.

The species vulnerability index used in ACCELERATES has been described in more detail elsewhere, but a brief summary of the method follows. The index uses the outputs of the SPECIES model to derive the sensitivity and adaptive capacity of species to climate change and is applied at the European and regional scales. The SPECIES model uses an artificial neural network to integrate bioclimatic variables for simulating the current distribution of species through the characterisation of bioclimatic envelopes (see Harrison et al., 2006 and Pearson et al., 2002 for a detailed model description). The model is then run under alternative climate change scenarios to predict the potential re-distribution of the species in the future. As listed in Harrison et al. (2006), 47 species were chosen to encompass a range of taxa and dominant and threatened (sensitive/rare) species from habitats affected by climate change and agricultural land use change. The outputs from these model runs are used in the calculation of the species vulnerability index.

The sensitivity of a species is calculated using the relationship between the current and potential future distribution and their degree of overlap. Sensitivity is a function of the amount of change in suitable climate space, which is measured in terms of four species' indicators: gained climate space; lost climate space; overlap between present and future climate space; size of the future distribution (Fig. 1). It is important to separate the gains and losses, as the losses in suitable climate space at the southern range margin in Europe can cancel out the gains at the northern range margin, leading to a small overall change in species' range and hence a low sensitivity score. The sensitivity indicators are calculated as follows, where *base* is the number of 10′ grid cells currently occupied by the species in Europe, *scenario* is the number of grid cells modelled as suitable climate space under the scenarios and *overlap* is the number of cells common to both *base* and *scenario*:

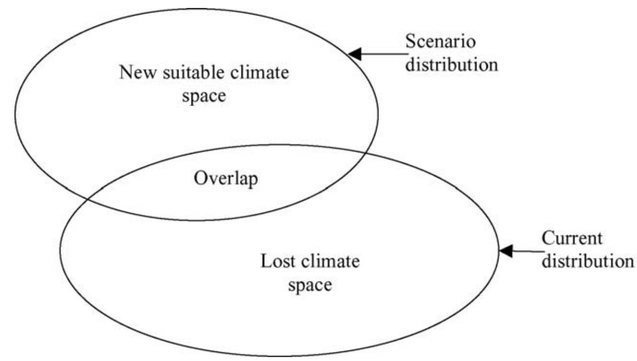

Fig. 1 – Schema illustrating how climate space is used to calculate the sensitivity indicators.

Indicator *A* — new climate space: (scenario − overlap)/base × 100;
Indicator *B* — overlap between present and future climate space: (overlap/base) × 100;
Indicator *C* — lost climate space: (base − overlap)/base × 100;
Indicator *D* — size of future suitable climate space: (scenario/total area) × 100.

The percentage changes in climate space for indicators *A* to *C* are calculated using the current distribution as base, rather than the total area under consideration (Europe or the country) as the denominator, otherwise rare species only show a small percentage change and thus score poorly. This means that only indicator *D* has a common denominator for inter-species comparison.

The scoring system for each indicator is detailed in Table 2. It is based on ecological understanding of the effects of change of range size (either actual or potential) on species' vulnerability and the likelihood of such changes being realised. The actual scores are based on expert opinion and have been discussed with appropriate stakeholders.

Table 2 – Scoring system for the species' sensitivity indicators (%)

Score	Indicator *A*	Indicator *B*	Indicator *C*	Indicator *D*
0	$A \geq 100$	$B \geq 100$	$C \leq 0$	$D > 50$
1	$75 < A < 100$	$75 < B < 100$	$0 < C < 25$	$40 < D \leq 50$
2	$50 < A \leq 50$	$50 < B \leq 75$	$25 \leq C < 50$	$25 < D \leq 40$
3	$25 < A \leq 50$	$25 < B \leq 50$	$50 \leq C < 75$	$10 < D \leq 25$
4	$0 < A \leq 25$	$0 < B \leq 25$	$75 \leq C < 90$	$1 < D \leq 10$
5	$A \leq 0$	$B \leq 0$	$C \geq 90$	$D \leq 1$

Table 3 – A comparison of the approaches to assessing agricultural land use and species vulnerability

	Agricultural land use	Species
Sensitivity indicator	Changes in area of intensive, extensive and abandoned land, as a function of farmer profit	Area of new climate space Area of overlap between current and new climate space Area of lost climate space Area of future suitable climate space
Adaptation	Autonomous adaptation is implicit on calculation of agricultural land use change and planned is implicit in the qualitative assessment	Explicit through species dispersal or planned human action
Vulnerability	Implicit qualitative assessment	Explicit function of sensitivity and adaptation

Two vulnerability indices are calculated from the species' sensitivity indicators. Index VA assumes no planned adaptation consistent with the A1FI and A2 SRES storylines, where humans have little concern for the environment. VB includes autonomous and planned adaptation, and is assumed to occur under the B1 and B2 SRES storylines (VB), where sustainability, equity and environment are of concern. For index VB it is assumed that a species can make full use of its new climate space either by autonomous or planned adaptation.

A species' autonomous adaptation through dispersal is thought to be variable and limited (Collingham and Huntley, 2000; Berry et al., 2005; Pearson and Dawson, 2005), thus it will require human intervention (planned adaptation) through translocation (Edgar et al., 2005), an increase in the number and/or size of protected areas, habitat recreation or through the removal of other external stresses on species, such as pollution, habitat destruction and fragmentation.

The degree to which planned adaptation can be implemented is assumed to be a function of the extent of new climate space, as this indicates the limit of the species' potential future distribution. Thus, index VB uses the full scoring system for indicator *A* (new climate space) shown in Table 2, as it assumes that full adaptation occurs. It is calculated by summing indicators *A* to *D*.

In contrast, index VA assumes that none of the new climate space can be utilised by a species as autonomous adaptation is assumed to be restricted to within the boundaries of the 10′ grid cells, which the species currently occupies, due to limited dispersal and there is no new planned adaptation. Hence, indicator *A* is fixed at the maximum value of 5 before indicators *A* to *D* are summed for computing VA. A not dissimilar approach has been used in other research concerned with the ability of species to fulfil their future climate space (Thomas et al., 2004; Thuiller et al., 2005). VA and VB represent, therefore, the extremes of the potential adaptive capacity of species and were calculated for the whole of Europe.

The relationship between the two vulnerability assessments is detailed in Table 3 and conceptualised in Fig. 2 and shows how the vulnerability of farmers can mitigate or reenforce climate change induced species vulnerability. This also shows the scope for policy intervention and planned adaptation in reducing a species' vulnerability under climate change.

3. Results

3.1. *European farmer vulnerability*

Figs. 3–5 show the change in intensive, extensive and abandoned agricultural land, respectively, and how the agricultural systems and farmer vulnerability might change under a range of alternative HadCM3 scenarios. For the HadCM3 A1FI + WM scenario, intensive land use increases at higher latitudes (i.e. in Scandinavia, especially southern Finland) and also at higher altitudes (i.e. Trentino, Italy) due to the beneficial effects of warming. Decreases in intensification occur at lower latitudes (i.e. southwest France, Spain, Portugal and Italy), where higher temperatures and

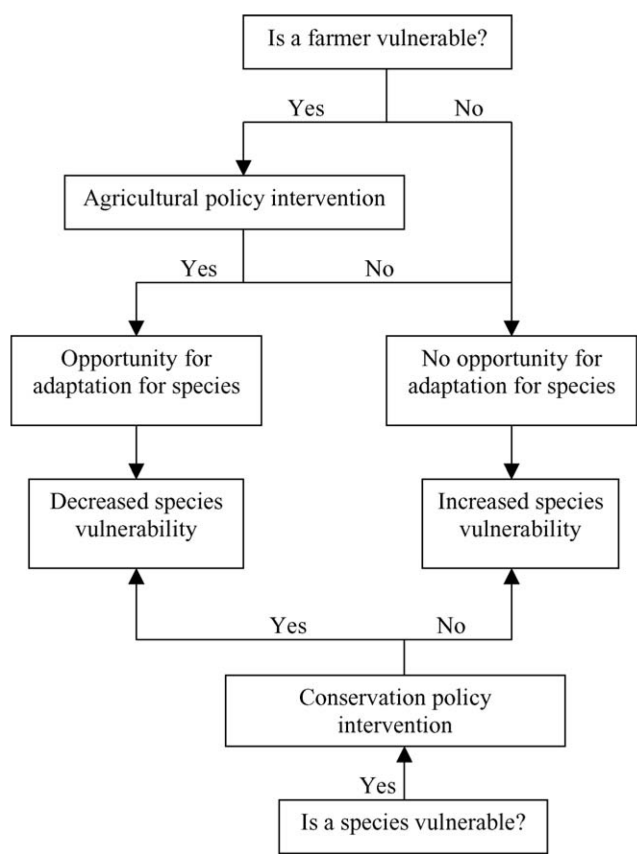

Fig. 2 – Schema illustrating the relationship between the vulnerability assessments for farmers and for species.

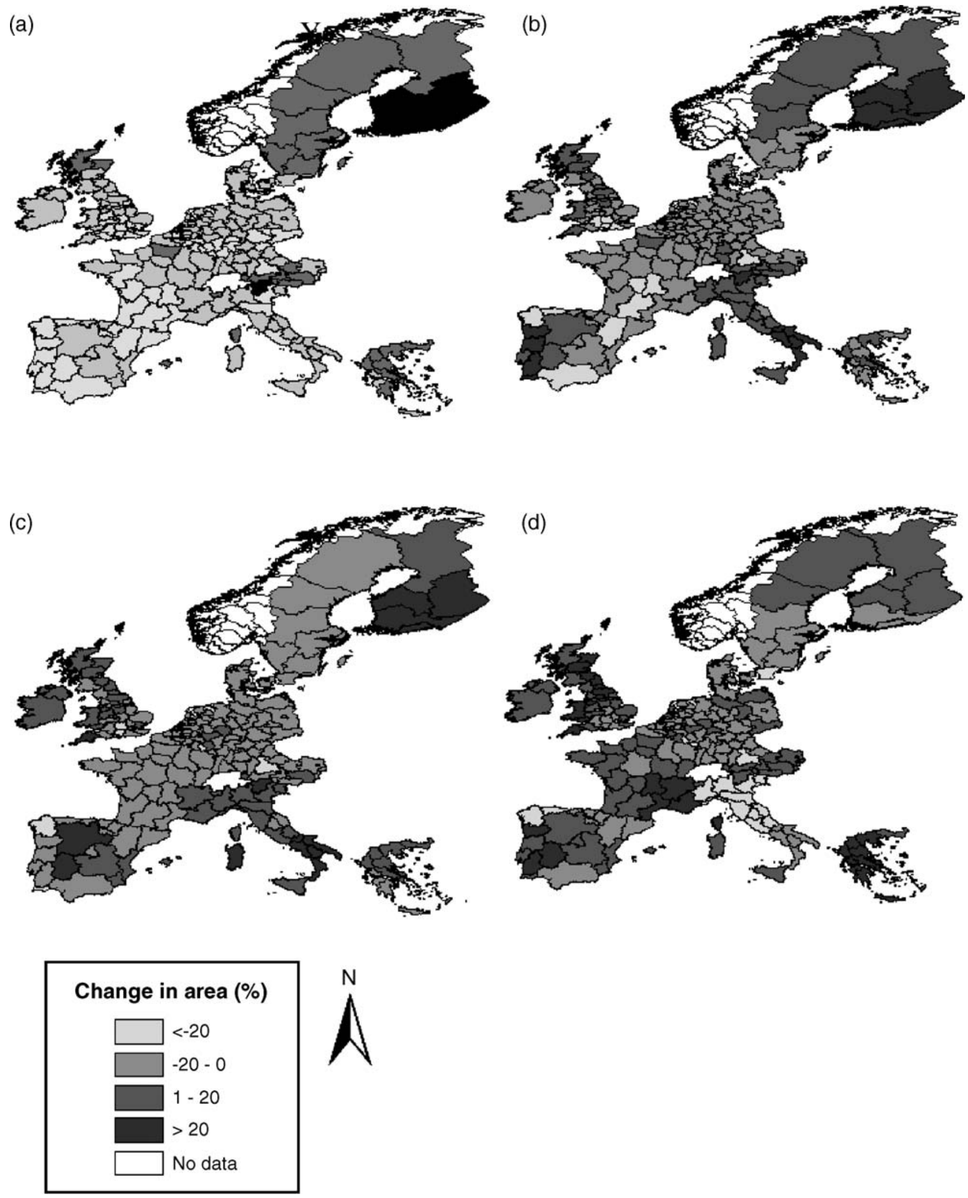

Fig. 3 – Change in area of intensive agricultural land use for the HadCM3 scenarios in 2050: (a) A1FI + WM, (b) A2 + RE, (c) B1 + GS and (d) B2 + LS.

incre-ased aridity have a negative effect on farm profitability. Some mid-latitude regions (i.e. the southern UK, southern Belgium, Luxembourg and parts of Germany) also show strong decreases in intensification. These trends are reflected in the maps of extensive and abandoned agricultural land with abandonment becoming widespread in currently marginal areas.

Within the framework of a free market driven scenario, the capacity for planned adaptation would be limited. Production and rural development subsidies would not be available, so that farmers in regions where profits decrease (becoming less intensive) would be very vulnerable (i.e. the areas of more extensive or abandoned agriculture). A low appreciation of environmental concerns could result in the unconstrained expansion of agriculture into previously uncultivated areas at higher latitudes and altitudes. Whether this would occur in practice when agricultural areas elsewhere in Europe are reducing (e.g. see Rounsevell et al., 2005) is debatable, however, it remains a possibility. Agricultural expansion would benefit farmers in such areas, but would probably have negative impacts on biological resources.

The trends for the HadCM3 A2 + RE scenario are similar to A1FI + WM, with high latitude and altitude areas becoming more intensive. However, A2 + RE shows more intensification everywhere, which can be explained by the higher prices, subsidies and much lower labour costs assumed for the RE economic scenario compared with the WM economic scenario. Parts of southern Europe (notably southern Italy and Portugal) even become more intensive compared with the baseline, which is the opposite situation to the A1FI + WM scenario. This can be explained by the different spatial

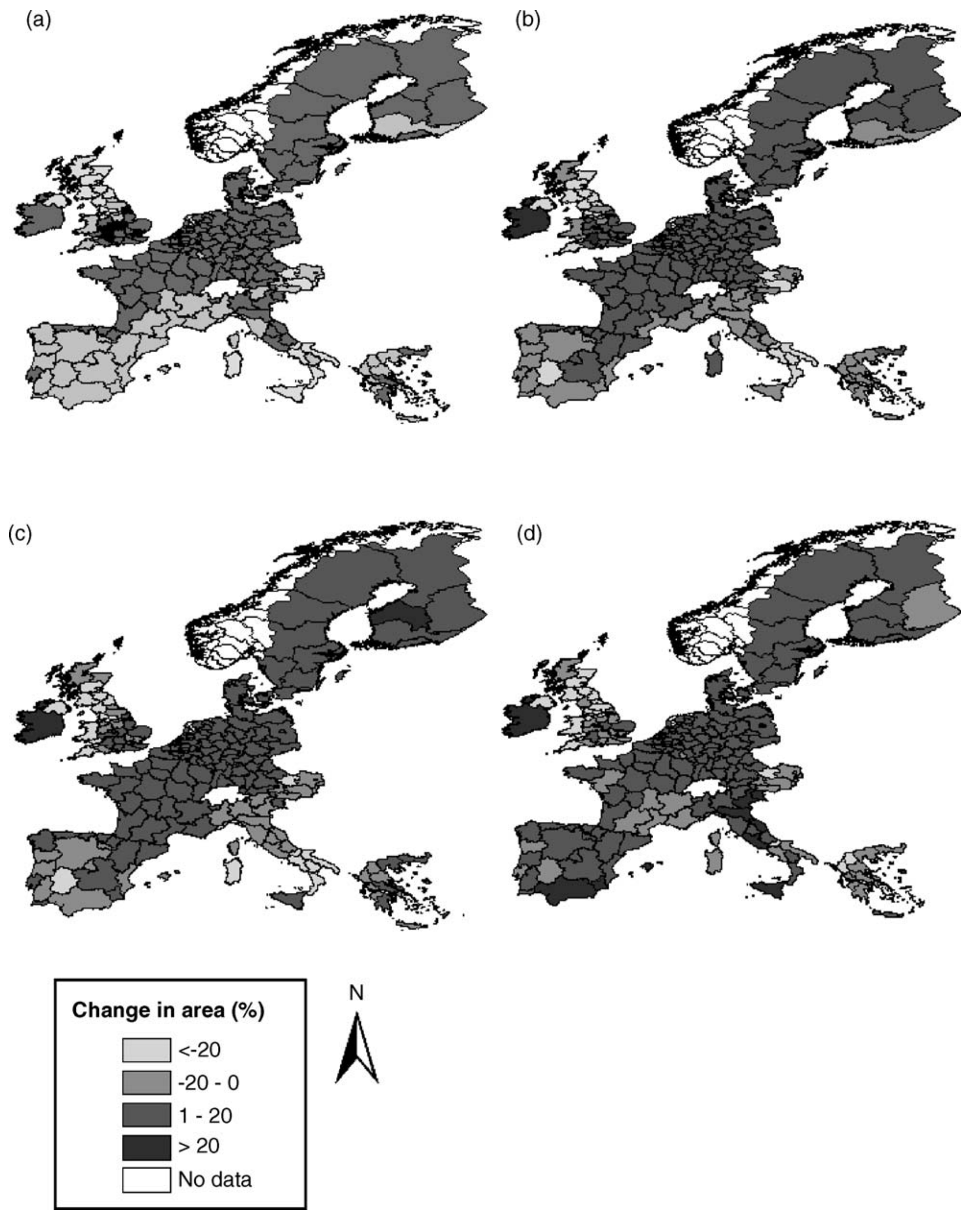

Fig. 4 – Change in area of extensive agricultural land use for the HadCM3 scenarios in 2050: (a) A1FI + WM, (b) A2 + RE, (c) B1 + GS and (d) B2 + LS.

patterns of climate change in the HadCM3 A2 climate scenario.

Abandonment again tends to occur in marginal agricultural areas and is at its greatest in the A2 + RE scenario, although Ireland becomes more extensive. Adaptation to these changes would be different for an A2 + RE world than for an A1FI + WM world. As a regional scenario, marginal agricultural areas probably would be, to some extent, protected in order to maintain regional production and the local rural character. Thus, areas that might be abandoned are less likely to be so and are consequently less vulnerable compared with the same areas in the A1FI + WM scenario. As an economic scenario, new opportunities for agricultural production at higher latitudes would probably be encouraged to the benefit of farmers, but with potential environmental impacts.

Intensification in the HadCM3 B1 + GS scenario increases slightly almost everywhere, including southern Europe, although southern Finland and southern Italy again show the biggest increases. This probably reflects the slightly higher levels of commodity prices, the less severe climatic change and the technological gains for crop yields. As a consequence abandonment is less important for the B1 + GS scenario compared with the others and farmers on the whole would enjoy relatively good levels of profitability and are, therefore less vulnerable. Because B1 + GS is an environmental scenario, it is assumed that the northward expansion of agriculture would be restricted through appropriate policy measures. Thus, on the whole, the B1 + GS scenario has the greatest net benefits of all the scenarios in terms of maintaining farmer incomes (mini-

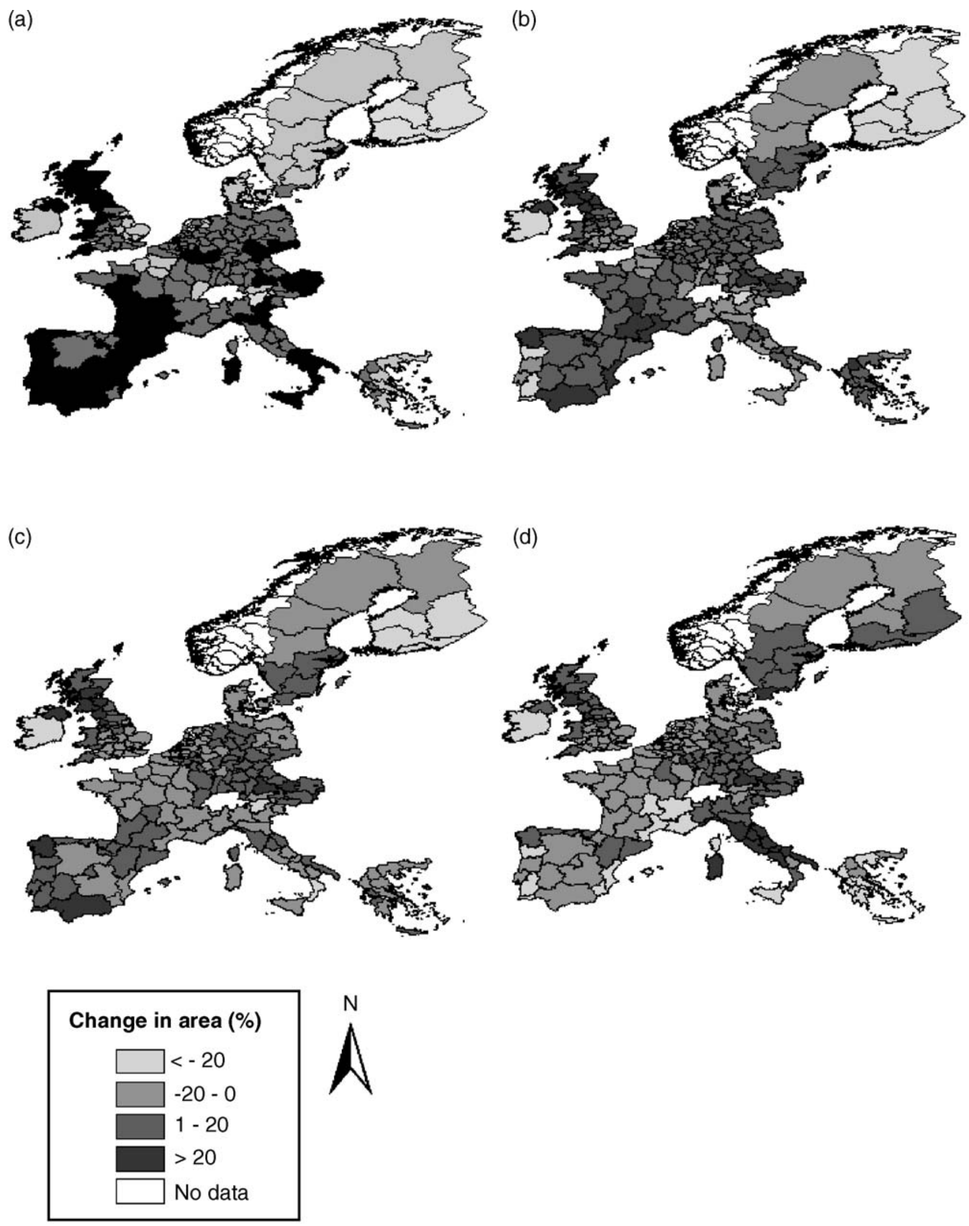

Fig. 5 – Change in area of abandoned agricultural land for the HadCM3 scenarios in 2050: (a) A1FI + WM, (b) A2 + RE, (c) B1 + GS and (d) B2 + LS.

mising farmer vulnerability) and limiting environmental impacts.

Intensification in the HadCM3 B2 + LS scenario is quite different from the other scenarios. Scandinavia no longer has increased intensification, whereas southern Europe (with the exception of northern Italy) does. Southern France, Portugal and the north and west of the UK show the greatest increases in intensification. This reflects the patterns of climate change for the HadCM3 B2 climate scenario with northern latitudes not becoming sufficiently warm for intensive agriculture to be profitable. The other observations reflect the spatial variability in precipitation patterns. Yield gains due to technological development are, however, assumed to be the lowest for this scenario, and this strongly affects profitability.

In terms of adaptation, society within a regional and environmentally orientated world is likely to seek both to minimise abandonment and intensification, but encourage extensification through policy support measures. This would limit the vulnerability of farmers, but the weaker economic and technological development assumed in this scenario could limit the scope and effectiveness of potential adaptation options. Thus, the vulnerability of farmers within a B2 + LS world is considered to be greater than the vulnerability within a B1 + GS world.

Fig. 6 shows the change in the three land use categories (intensive, extensive and abandoned land) in 2050 for the A2 (+RE) scenario based on the PCM GCM. In general, these maps show similar trends to the equivalent maps for the A2 scenario based on the HadCM3 model (see Figs. 3–5), although the

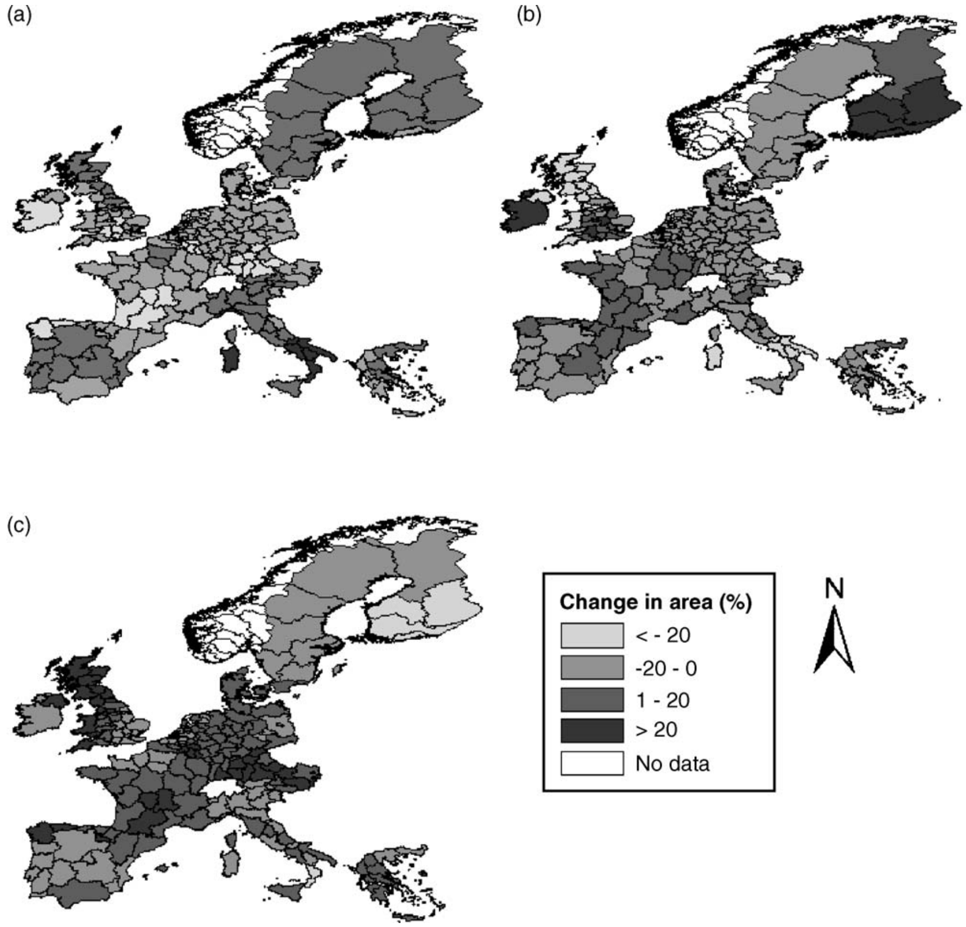

Fig. 6 – Change in area of (a) intensive agriculture, (b) extensive agriculture and (c) abandoned agricultural land for the PCM GCM (A2 + RE scenario) in 2050.

magnitude of change is generally less for the PCM model. The PCM scenario runs were based on exactly the same socio-economic scenario assumptions as the HadCM3 runs. The only difference between the scenarios is due to the climate with the PCM model projecting a less severe climate change (in terms of temperature) than the HadCM3 model. The difference between these scenarios shows, therefore, that the more severe HadCM3 climate change increases the magnitude of the effects of socio-economic change on land use.

Table 4 shows the total area of agricultural land that is abandoned in the EU15 under the various HadCM3 scenarios. As indicated by the maps in Fig. 5, the A1FI + WM scenario has by far the largest increase in abandoned agricultural land. The A2 + RE scenario shows a slight increase, but all other scenarios show very little change: the B1 + GS scenario even has a slight expansion in agricultural land, although this is a very weak change. The abandonment of agricultural land in the A1FI + WM scenario reflects the more severe climatic conditions of this scenario combined with a difficult economic environment (in terms of the assumed price and cost changes). The level of abandonment is, however, consistent with the results from other studies. For example, Rounsevell et al. (2005; in review) suggested agricultural land abandonment in 2050 for the A1FI scenario to be about 25% of the agricultural area, including an assumed shift from the production of food to the production of bioenergy of about 5% of the agricultural area. They also found very little change in land abandonment for the B1 and B2 scenarios. Conversely, however, Rounsevell et al. (2005; in review) suggested that the A2 scenario would have a similar level of land abandonment to their A1FI scenario (ca. 25%), which is not the case for the results presented here. Whilst this difference probably reflects alternative interpretations of the SRES scenarios, it is striking how similar the other scenario results are, especially when one considers that the two studies were based on conceptually very different approaches to land use change modelling.

Table 4 – The area of abandoned agricultural land in the EU15 (% of agricultural area) for each SRES scenario and the HadCM3 and PCM GCMs in 2050

	A1FI	A2	B1	B2
HadCM3	19.97	3.14	−0.07[a]	0.05
PCM	–	0.04	–	–

[a] Represents a net expansion in the agricultural land area.

Table 5 – Number of species classified into four vulnerability groups based on their index scores under different climate change scenarios for Europe

Vulnerability score	HadCM3 A2 scenario						PCM A2 scenario					
	VA			VB			VA			VB		
	2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080
Not vuln (0–5)	0	0	0	5	9	9	0	0	0	3	10	11
Slight (6–10)	42	37	32	40	35	27	45	43	41	44	36	34
High (11–15)	5	10	14	2	3	11	2	4	6	0	1	2
Extremely (16–20)	0	0	1	0	0	0	0	0	0	0	0	0

3.2. *European species' vulnerability*

Table 5 shows that through time, under the HadCM3 A2 scenario (VA index), the vulnerability of species in Europe increases. This is due to increasing sensitivity, through loss of overlap of current and future climate space, loss of current climate space and a reduced future distribution, which can lead to potential rarity. For *Genista pilosa* (Hairy greenweed) for example, VA increases from 9 to 13 as the overlap decreases (77–31%), lost climate space increases (23–69%) and the European distribution decreases (39–26%) (Fig. 7).

Index VB for the HadCM3 B1 scenario is generally lower than VA for more southern species, such as *Olea europaea* (Olive) and *Nerium oleander* (Oleander), which benefit from new climate space (Fig. 8). However, it remains similar to VA for more northern species, such as *Vaccinium myrtillus* (Bilberry) and *Rubus chamaemorus* (Cloudberry) which are unable to expand as they are already at their northern limits (Fig. 9) or appear to be very sensitive, such as *Crex crex* (Corncrake). This demonstrates the importance of adaptation in reducing vulnerability for many species, but highlights that there will be little opportunity for planned adaptation for those species already at their northern range margins which have nowhere to go.

The species vulnerability analysis suggests that without planned adaptation, as assumed under the A2 scenario, the vulnerability of many species in Europe will increase. This underlines the importance of adaptation in reducing vulnerability for these species. Climate space is not totally lost at the European scale for any of the modelled species, thus vulnerability will be experienced at a regional to national scale. Scandinavia, for example, will become increasingly important for species, such as *Grus grus* (Common crane) Where climate space is predicted to be totally lost from a

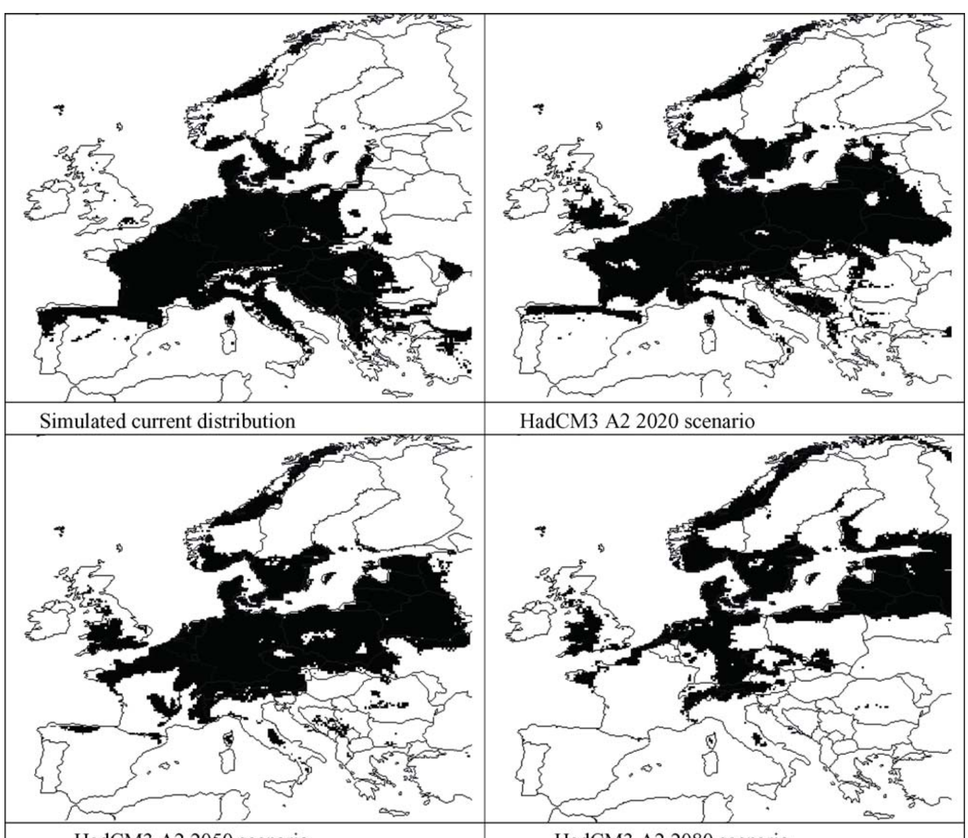

Fig. 7 – Change in suitable climate space for *Genista pilosa* under the HadCM3 scenarios.

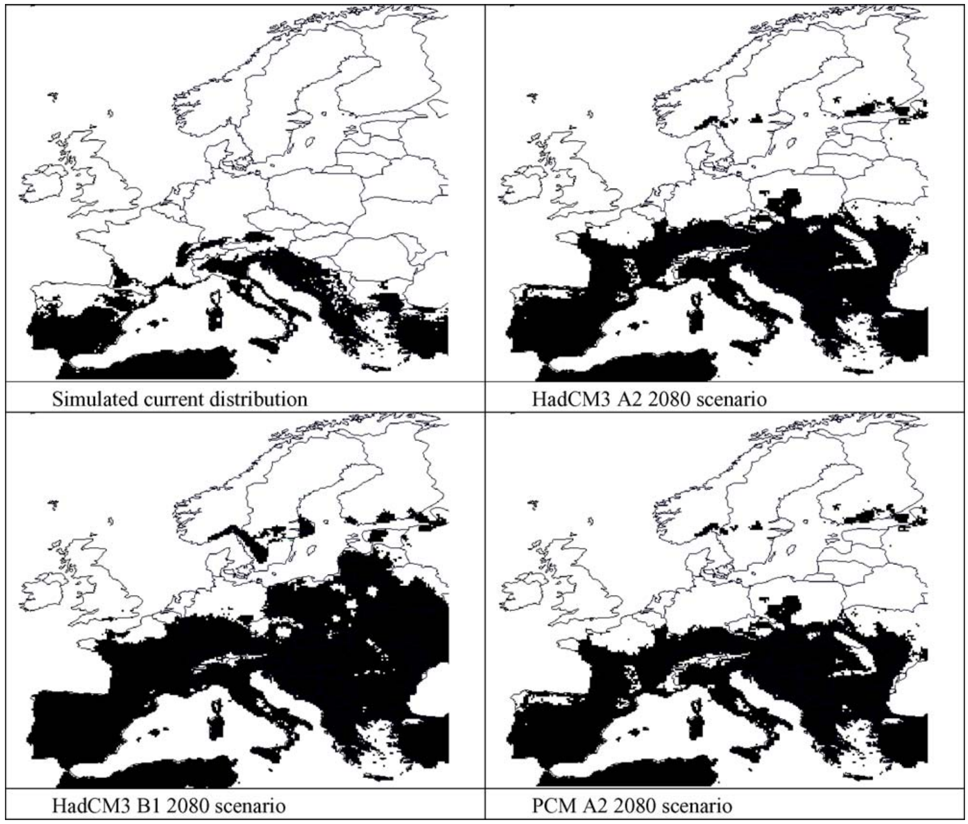

Fig. 8 – Change in suitable climate space for *Nerium oleander* under different climate change scenarios.

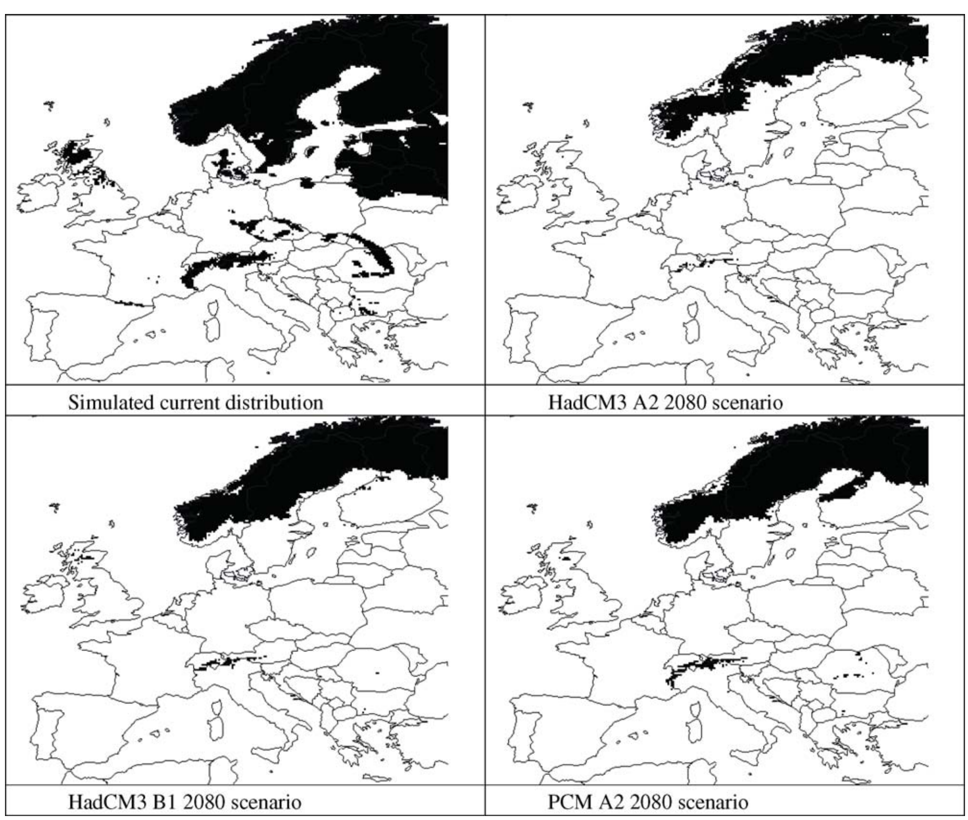

Fig. 9 – Change in suitable climate space for *Rubus chamaemorus* under different climate change scenarios.

country thought needs to be given to ensuring that these species become a conservation priority in those countries which remain suitable, usually those to the north(east).

In the case of northern species at the European scale there is only a limited range of adaptation options, due to no new suitable climate space becoming available. In such instances, management to reduce any stresses and to maintain the habitat in, or restore it to favourable conservation status is the only option. The interpretation of the agricultural land use suggests that the northward expansion of agriculture might be restricted by policy measures under the HadCM3 B1 + GS scenario, thus leaving opportunities for the implementation of appropriate conservation measures.

Where losses occur at the southern range margin, e.g. *R. chamaemorus* in Denmark, it may be appropriate to accept such losses, but to ensure that its conservation is secure in areas further north. In other instances, where species need to disperse in order to remain within their climate envelope, then the removal of barriers to migration, especially the development of a ''permeable'' landscape to enhance such movement would be important. This could include the re-creation of habitats, the favourable management of intervening land or the expansion of existing protected areas and is an example of planned adaptation facilitating autonomous adaptation. Another option would be the translocation of species, but this is expensive and fraught with difficulties and is only appropriate in exceptional circumstances.

4. Discussion and policy implications include something on exposure

The use of two GCMs and four SRES scenarios enabled only some of the range of climate and emissions scenario uncertainty to be considered. Nevertheless as the aim of this paper was to test the application of vulnerability indices and explore the need for integration across the two sectors this should not be a major problem, but should be borne in mind when interpreting the results.

The limitations of the bioclimate envelope models to simulating changes in suitable climate space have been discussed elsewhere (Pearson and Dawson, 2003; Hampe, 2004). These studies conclude that at the continental scale climate is the dominant factor affecting species' distributions and thus they provide a valid approach in the context of Europe. For application at smaller spatial scales, factors, such as dispersal, competition and evolutionary change, would need to be considered (Pearson and Dawson, 2003). In this paper only one model (SPECIES) has been used, thus uncertainty from the modelling technique has not been explored, but previous studies comparing the predictive performance of bioclimate envelope modelling techniques have concluded that neural networks generally provide more accurate predictions of species range shifts than other widely used methods (Segurado and Araujo, 2004; Thuiller, 2004; Pearson et al., in press; Araújo et al., 2005).

The vulnerability assessment for agriculture showed a reduction in the vulnerability of farmers in northern Europe, as crop suitability and yields increase under the HadCM3 A1F1 + WM and A2 + RE scenarios. This increasing pressure of intensification at higher latitudes and altitudes may or may not be realised according to the assumed policy context. Farmers in currently marginal areas further south in Europe seem vulnerable within most scenarios, although again the magnitude of the effect will depend on the willingness for policy intervention. It is difficult to say, however, which of the marginal agricultural regions are the most vulnerable to change as the spatial patterns of change vary greatly between the scenarios.

The species results show that the importance of the sensitivity indicators varies between species. This is dependent on their location and range size, with those with a northern distribution and small range being particularly vulnerable. Species with high vulnerability are of conservation concern, and adaptation management and policies to reduce their vulnerability need to be put in place.

The apparent vulnerability of species to climate change needs to link more strongly with other land uses, given the potential widespread increase in species vulnerability. There is a particularly important role for agriculture here as this is the land use in Europe with the largest areal extent, and thus it is central to safeguarding biodiversity. The land use vulnerability has shown that there is a potential for further loss of suitable habitat for species, particularly under the A1FI climate scenario, as areas which had been less intensively managed or in a semi-natural condition are used for agriculture. This would support the concerns of Parmesan and Yohe (2003) that over the short-term land use change will be an important driver of local biological changes and this will increase species' vulnerability.

These concerns about the impact of land use change on species' vulnerability, however, are dependent on the region and the climate and socio-economic scenario under consideration. Under the HadCM3 A2 climate scenario, for example, surplus (agricultural) land, as a consequence of about a 50% reduction in European food production areas, is estimated to occur (Ewert et al., 2005; Rounsevell et al., 2005). This represents opportunities for the purchase and management of land for biodiversity, so that protected areas could be set in a more favourable and connected matrix. There is a paradox here in that the socio-economic scenario that would give rise to this (RE) is one that conservation organisations may not wish to promote, as it is a consequence of high greenhouse gas emissions.

Surplus land also gives an opportunity for habitat re-creation and this could assist national conservation policies, such as the U.K. Biodiversity Action Plans, to achieve their targets. This depends on the location of surplus land in suitable locations and available finance for the purchase of appropriate land areas. The B2 + LS scenario leads to opportunities for agricultural extensification. This too could reduce further habitat losses, as well as making appropriate habitat management easier, by a reduction in fertiliser and pesticide usage or grazing and increased opportunities for new protected areas, habitat re-creation and restoration. This could potentially reduce species vulnerability, but once again there is an irony, as this scenario generally leads to increased farmer vulnerability. In the future, therefore, there may be conflict, where policy has a choice of protecting farmers or protecting species, and rationalising these two policy objectives is difficult.

To return to the two questions posed earlier: (a) what determines the relationship between a change (scenario) and its effects? (b) who or what is vulnerable and where are the vulnerable located? For both agriculture and biodiversity, the relationship between changes derived from the scenarios and their impacts is a function of the sensitivity of the systems to the degree of exposure, as shown by their different responses. It is also the result of the resilience or adaptive capacity of the system, much of which may be determined by policy. For example, for agriculture the socio-economic scenarios were mostly responsible for the different patterns of land use change. Species' vulnerability, however, was largely determined by their response to the climate scenario; the scenarios exhibiting the greatest changes in temperature and precipitation (HadCM3 A1FI and A2) usually leading to higher vulnerability. This may partly be a result of the SPECIES model being based on climate parameters and partly that the distribution of species is largely a function of climate at the continental scale (Pearson and Dawson, 2003). At smaller spatial scales other factors, such as land use, soil type, topography and biotic interactions, can become more important (Pearson and Dawson, 2003).

In the case of farmers, the adaptive capacity was assumed to depend on the flexibility of cropping system and the willingness of society to intervene through policy. For species, the difference between the two vulnerability indices shows that, where there are large amounts of new climate space, then adaptation is an option, but its realisation is dependent on the socio-economic scenario. The difference between the two indices is often much less than the maximum of five, indicating that adaptation often only made a limited contribution to reducing species' vulnerability.

The geography of the vulnerability is also variable, due to the different patterns of exposure produced by the climate scenarios, the ability of socio-economic systems to adapt and the policy response. For agriculture, the marginality of farmers is dependent on policy intervention, although some currently marginal areas in northern Europe could see an increase in productivity and thus reduced farmer vulnerability. For species, policy also has an important part to play in aiding planned adaptation and facilitating autonomous adaptation. Attention, therefore, must be given to reviewing agricultural and conservation policy in the light of climate change, with a view to decreasing vulnerability at all levels. This work has also shown that, in order to respond appropriately to climate change impacts, sectoral integration for policy development is crucial. The reform of CAP and the EC-Agricultural Action Plan on Biodiversity, for example, must ensure that they incorporate appropriate policy recommendations and flexibility to deal with the potential impacts of climate change on farmers and species, in an integrated manner.

5. Conclusions

This paper has shown that climate change will impact on the vulnerability of both agriculture and species, and this will vary according to the scenario, the region or species under consideration. It is, however, vital that these two are examined together as potential changes in agriculture can impact both directly and indirectly on the vulnerability of species, by affecting their ability to adapt, either beneficially (through extensification or land abandonment facilitating species movement, habitat re-creation and landscape connectivity) or negatively (through intensification resulting in loss or reduced quality and fragmentation of habitats). The current policies for agriculture or biodiversity rarely take explicit account of climate change and yet in the future this will be an important driver of changes in both these sectors, with those in agriculture either re-enforcing or mitigating the changes in biodiversity vulnerability. A combined approach to the assessment of vulnerability for agriculture (farmers) and species is important if appropriate policy measures are to be implemented in response to climate change, as changes in agricultural land use may provide opportunities for planned adaptation for species (e.g. land use extensification and abandonment), but this may be to the detriment of farmers. Policy will need to rationalise these potential conflicts between farmer and species vulnerabilities.

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Eric Audsley has over 30 years experience of applying mathematical, operational research and systems modelling techniques to the analysis and optimization of decisions concerning agricultural systems. One of his main areas is the application of linear programming to whole farm modelling to allow complete flexibility of optimal choice of cropping and machinery, constrained only by agronomic and physical factors. Models have been developed for arable, horticultural and grass farm systems, for decision making with uncertainty, and for calculating environmental emissions as a function of the type and timing of operations, with multiple objective optimization.