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Cross-sectoral impacts of climate and socio-economic change in Scotland: implications for adaptation policy

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Abstract Understanding the importance of cross-sectoral implications of climate and socio-economic change in Scotland is essential for adaptation policy. This study explored the direct and indirect sectoral impacts of future change using the CLIMSAVE Integrated Assessment Platform. There is great spatial diversity in projected impacts across Scotland, and increasing uncertainty in the direction of change of impacts from the national to regional scale associated with climate uncertainty. Further uncertainty associated with socio-economic change results in 6 out of 13 indicators (artificial surfaces, biodiversity vulnerability, forest area, land-use intensity, irrigation usage and land-use diversity) with robust directions of change at the national scale and only three (artificial surfaces, forest area and irrigation usage) that are robust across all regions of Scotland. Complex interactions between socio-economic scenario assumptions (e.g. food imports, population and GDP), climatic suitability and agricultural productivity and profitability lead to significant national and regional changes in the distribution and extent of land cover types, with resultant cross-sectoral interactions with water, forestry and biodiversity. Consequently, stakeholders characterised robust adaptation policy options, within the CLIMSAVE participatory process, as those beneficial to society (and the country) in all scenarios, irrespective of the direction of change of the impacts. The integration in CLIMSAVE of a participatory scenario development process and an integrated participatory modelling framework has allowed the exploration of future uncertainty in a structured approach and better represented the importance of qualitative information and the social and institutional contexts within adaptation research.

Keywords Cross-sectoral · Participatory · Integrated assessment · Impacts · Adaptation · UK

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Introduction

Society derives many benefits or ecosystem services from the natural environment and its constituent resources (MA 2005). It is increasingly recognised that the state of these resources, and thus the benefits derived by society, may be modified by both non-climate and climatic pressures at regional/subnational (Holman et al. 2008) and national scales (Harrison et al. 2013; Rounsevell et al. 2006). Given the economic drivers of land management, previous research has suggested that non-climatic pressures such as future socio-economic change may be more important than climate change (Holman et al. 2005; Rounsevell and Reay 2009), but there are many compounding and interacting effects such that changes in one sector can affect another sector either directly, e.g. changes in land use affect regional hydrology or biodiversity (Audsley et al. 2008;

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Harrison et al. 2008), or indirectly through policy, e.g. measures designed for coastal flood defence impacting on coastal habitats (Mokrech et al. 2008). Omitting such cross-sectoral interactions can lead to the over- or under-estimation of climate change impacts and adaptation costing (Skourtos et al. 2014) and therefore affect adaptation decisions (Carter et al. 2007).

Scotland is a country within the UK that is rich in natural resources and associated ecosystem services, but potentially sensitive to both the adverse and beneficial impacts of climate change. This arises from, for example, its current climate being marginal for agriculture in many parts of the country (Brown et al. 2011), but also that important components of its biodiversity are at the margins of their climate suitability (Trivedi et al. 2008). Adaptation therefore represents an important opportunity for Scotland to reduce the adverse impacts and to exploit the beneficial opportunities to the advantage of Scottish society (Scottish Government 2009). Furthermore, limitations in the recognition of cross-sectoral interdependencies can leave society and government vulnerable to the dangers of conflicted or unintended adaptation policy outcomes from sectoral decisions. However, climate change adaptation is a complex human-environmental problem that is framed by the uncertainty in impacts and the adaptation choices available, but also bounded by real-world constraints such as future resource availability and environmental and institutional capacities (Hinkel and Bisaro 2014).

Adequately assessing such issues of global environmental changes requires understanding innately regional phenomena within an integrated framework (Hibbard and Janetos 2013). To this end, Hinkel and Bisaro (2014) propose a Diagnostic Adaptation Framework that addresses the methodological choices (from practice approaches such as stakeholder consensus to research approaches such as impact projection) suitable for three key adaptation challenges of exploring risks; identifying measures and appraising options. Participatory scenario development processes play an increasingly significant role in such climate change studies (Alcamo 2008; Kok et al. 2011) and can play a crucial role in adaptation assessment by framing the different socio-economic trends that can form the context to long-term local or regional adaptation measures and in developing research results that inform political and societal decision-making and have practical application (Gramberger et al. in press).

This paper examines the multi- and cross-sectoral impacts of climate change and socio-economic change across Scotland, using a freely available interactive platform (the CLIMSAVE Integrated Assessment Platform—accessed through http://www.climsave.eu/iap) that integrates participatory scenario development and quantitative modelling. Direct and indirect sectoral impacts resulting from different scenario uncertainties are assessed. Finally, the implications of the simulated uncertainty in impacts on six sectors (agriculture, forests, biodiversity, water, coasts and urban) for the development of robust adaptation options are discussed.

Materials and methods

The CLIMSAVE IA Platform

The CLIMSAVE IA Platform is an interactive, exploratory web-based modelling tool to enable stakeholders to improve their understanding of impacts, adaptation responses and vulnerability under uncertain futures. The numerical models and underlying physical and scenario data sets use server-based web technologies to maximise access speed, whilst the web-based interface uses a client-based (i.e. the user's PC) computing solution to allow (i) fast reply to the user actions; (ii) output data from (server-based) models to be sent synchronously and asynchronously to the interface and (iii) the opportunity to use map services to display spatial data. Two versions of the CLIMSAVE IA Platform are freely available (www.clim save.eu/iap): one for Europe and one for Scotland (see Holman et al. 2013 for further information). This paper utilises the Scottish version.

Climate scenarios

The United Kingdom Climate Projections or UKCP09 scenarios (Murphy et al. 2009) are used within the Scottish IA Platform as these provide the greatest spatial and temporal detail for Scotland. They are probabilistic projections for three SRES emissions scenarios (A1FI—high emissions, A1b—medium and B1—low) based on ensembles of climate model projections consisting of multiple variants of the UK Met Office climate model, as well as climate models from other centres. In order to balance (1) an acceptable speed of operation of the platform, (2) capturing the uncertainty in the joint probability of projected temperature and precipitation changes and (3) making the number of scenarios manageable, the 10,000 probabilistic projections for each grid cell-emissions scenario-timeslice were sub-sampled to derive internally consistent climate scenarios (Table 1). One thousand projections centred on the 10th, 50th and 90th percentiles of average annual temperature change for each of the three emissions scenarios were further sub-sampled to identify the nearest 10 projections centred around their 10th, 50th and 90th percentiles of average winter and summer half-year precipitation (Fig. 1) based on guidance from the UK Climate Impacts Programme (Roger Street, *pers. comm.* 2011).

Table 1 UKCP09 climate projections for the 2050s used to characterise climate uncertainty, with (in parentheses) national-average changes for the three percentiles of annual temperature change and their associated summer and winter half-year (April–September; October–March, respectively) precipitation change percentiles

Emissions scenario	Annual temperature change percentile	Winter half-year precipitation change percentile	Summer half-year precipitation change percentile	Absolute UK Sea-level rise percentile
High	90th (3.3 °C)	10th (7.0 %)	10th (−12.0 %)	90th (36 cm)
High	90th (3.3 °C)	90th (24.3 %)	90th (3.6 %)	90th (36 cm)
High	50th (2.2 °C)	50th (13.4 %)	50th (−3.4 %)	50th (24 cm)
Low	50th (2.2 °C)	50th (9.2 %)	50th (−2.7 %)	50th (16 cm)
Low	10th (1.1 °C)	90th (15.0 %)	90th (5.4 %)	10th (8 cm)
Low	10th (1.1 °C)	10th (1.6 %)	10th (−8.6 %)	10th (8 cm)

Fig. 1 Overview of the methodology for deriving the subset of probabilistic climate changes scenarios for the Scotland
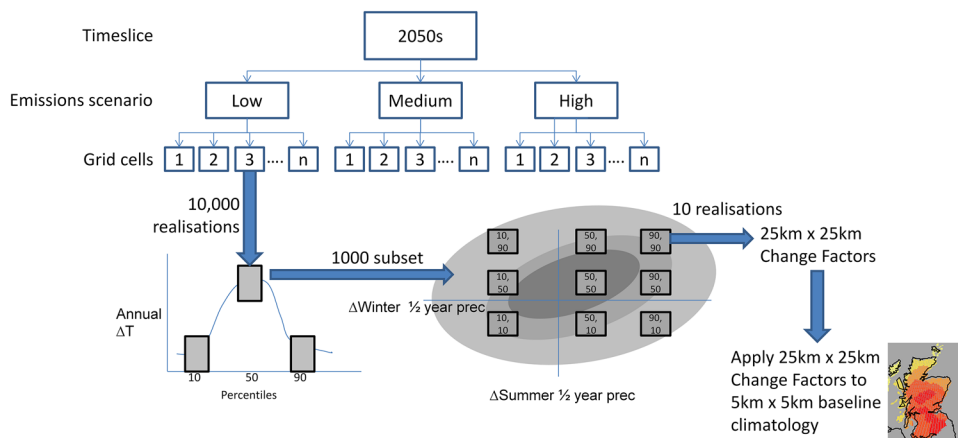
Absolute 10th, 50th and 90th percentile UK sea-level increases for each emissions scenario were obtained from UKCP09 (Table 1) and subsequently corrected for vertical land movement (using data from Bradley et al. 2011).

Socio-economic scenarios and the participatory process

Four socio-economic scenarios were developed by stakeholders within the CLIMSAVE project using a story-and-simulation (SAS) approach in which narrative stories are developed and linked to mathematical models in an iterative procedure (Kok et al. 2011; 2014). In addition, baseline socio-economics represented the current (2000–2010) period. A multi-level approach to stakeholder identification was used to identify representative organisations, and subsequently individuals, across a taxonomy of (1) sector of society [government, business, research, civil society]; (2) geographic level [national, regional] and (3) CLIMSAVE sectors (Gramberger et al. in press). In order to safeguard continuity, the same group of stakeholders were invited to each of the three professionally facilitated workshops, with replacements being either nominated or identified according to the selection process. In the first and second workshops, the objectively selected stakeholder group

developed and iterated qualitative socio-economic stories and dynamics according to the two drivers that they considered most important and uncertain: whether well-being and lifestyle were equitably distributed across Scottish society, and whether natural resources were in surplus or deficit. From these two axes, the four Scottish CLIMSAVE socio-economic scenarios are as follows:

- *"Tartan Spring"* (Surplus of natural resources, but a disparate human well-being and lifestyle.): a far-reaching, poorly regulated privatisation changes Scotland from a prosperous country with abundant resources to one with an eroded social fabric and a low standard of living, culminating in a "Tartan Spring" revolution.
- *"Mad Max"* (Deficit of natural resources and a disparate human well-being and lifestyle): driven by crises, a new self-centred paradigm emerges, which leads to a growing disparity in society. Day-to-day survival prevails, while new "clans" are ruling Scotland again.
- *"The Scottish Play"* (Deficit of natural resources, but equitable human well-being and lifestyle): building on traditional Scottish values, a lack of resources is dealt with by changes in lifestyle towards reducing, re-using and recycling, leading to a poorer but greener and happier population.

- "*MacTopia*" (Surplus of natural resources and an equitable human well-being and lifestyle): initially stimulated by a resource surplus, Scotland makes a transition towards an equitable and sustainable society to eventually become an IT, life sciences, green technology and finance frontrunner lead by a powerful middle class.

The qualitative stories and quantitative models were linked in a transparent and reproducible way using a "fuzzy set theory methodology" (Alcamo 2008; Kok et al. 2014) in the first and (refined in) the second workshops. With facilitation, each stakeholder derived numerical values that matched each of the linguistic descriptions of changes (e.g. "low", "medium" or "high") in key driving force variables (GDP, population, protected areas for nature, food import ratio, arable land used for biofuels, oil price and household size), for example, "'Low' GDP growth = 1–2 % per annum". These were applied to the linguistic term in each scenario to determine scenario-specific quantitative values (Kok et al. 2014; Online Resource 1) for each timeslice, expressed as relative to the value in the baseline (2000–2010) socio-economics that were subsequently used to inform expert-determined values of the remaining model inputs that were representative of the stakeholders' stories. In the second workshop, the stakeholders also identified potential adaptation options for their scenario, and the scenario-specific importance of those adaptation options included within the Platform. This importance was used to limit the ability to implement the given adaptation response in the IAP. In the final workshop (Gramberger et al. 2013), the stakeholders developed scenario-specific adaptation strategies, informed by their facilitated use of the Platform to model impacts and to test the effectiveness of adaptation (given the scenario-specific capital and storyline constraints), which were subsequently used to identify adaptation options that were robust to the socio-economic uncertainty.
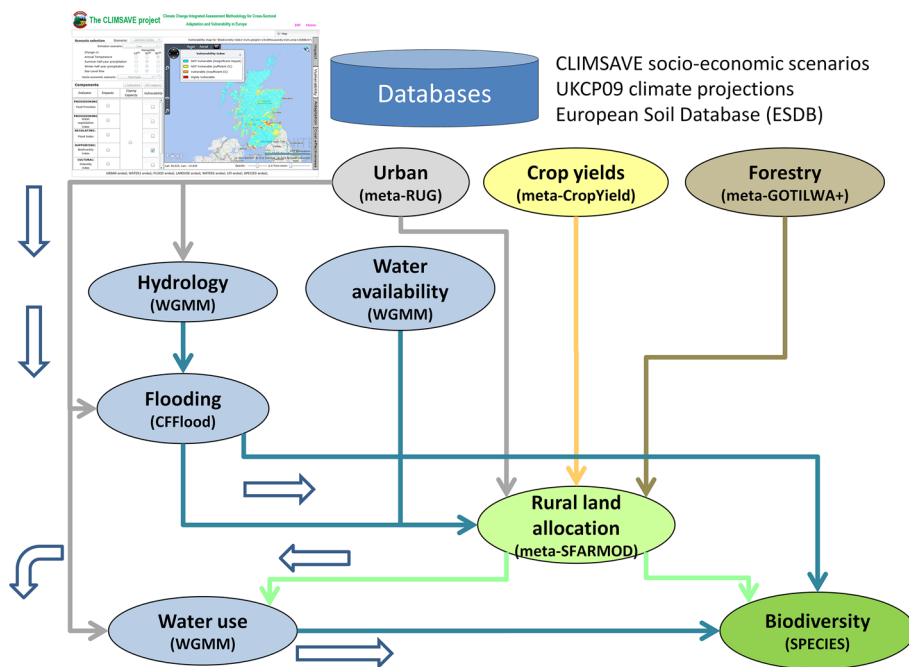
Models

Computationally efficient or reduced-form models that emulate the performance of more complex models (Holman et al. 2008) were developed using a variety of approaches to abstract the leanest representation for inclusion within the IA Platform that is consistent with delivering both functionality and speed (Holman and Harrison 2011; Harrison et al. 2013; Kebede et al. in press; additional information including references in Online Resource 1):

- Urban: the Regional Urban Growth (RUG) metamodel consists of a look-up table of artificial surfaces per grid cell derived from running the original RUG model with all possible combinations of Platform input values;

- Forest: MetaGOTILWA+ is an artificial neural network (ANNs) that emulates the performance of the GOTILWA+ model. The ANN was trained on GOTILWA results for 889 cells that spanned the range of environmental conditions across Europe;

- Flooding: the Coastal Fluvial Flood (CFFlood) metamodel is a simplified process-based model that identifies the area at risk of flooding based on topography, relative sea-level rise or change in peak river flow and the estimated Standard of Protection of flood defences. Flood damages for residential properties (both contents and structure) are calculated based on urban areas and people at risk of flooding, flood water depths and gross domestic product.

- Water: the WaterGAP metamodel (WGMM) uses look-up tables of 3 D response surfaces to reproduce the outputs of the WaterGAP3 model run at a $5' \times 5'$ resolution for about 100 spatial units (single large river basins or clusters of smaller, neighbouring river basins with similar hydro-geographic properties) larger than $10,000 \text{ km}^2$.

- Crops: the crop yield metamodels use ANNs, trained on simulated outputs of the ROIMPEL model, combined with temperature thresholds to prevent crops growing in unsuitable territories. The training data sets were sampled from 150,000 model data points to adequately cover the range of soil (Panagos et al. 2012) and climate predictors and the predictands.

- Rural land allocation: the SFARMOD metamodel uses a series of regression equations to simulate the behaviour of the full SFARMOD-LP model, using SFARMOD-LP outputs from 20,000 randomly selected sets of input data that fully cover the parameter input space. Up to 10 iterations based on profitability and food demand determine the final land allocation and food production.

- Biodiversity: SPECIES uses an ensemble of ANNs, utilising climate and soil moisture variables, to characterise bioclimatic suitability envelopes. The model is trained using empirical data on the European and North African (north of 15°N) distributions of species to enable the full climate space of species to be characterised.

All metamodels were satisfactorily validated against either baseline observations or against the validated outputs of the full model (see Holman and Harrison 2011 for the full details of each model and its validation; and Kebede et al. in press for a sensitivity analysis of the linked models within the IA Platform). The models are run at a resolution of 5 km × 5 km, consistent with the available baseline

Fig. 2 Simplified schematic showing data transfers between meta-models in the Scottish CLIMSAVE IA Platform (adapted from Harrison et al. 2013)

climatology. A simplified flow diagram of the linkages between the models is shown in Fig. 2. For example, outputs from the urban model on the location, extent and type of urban development affects river basin hydrological responses (water availability, peak flows, etc.), spatial water demand from the industrial and domestic sectors, the population in flood plains exposed to flood risk, the land available for agriculture and forestry and consequently habitat availability for biodiversity.

Outputs are produced for both sector-based impact indicators and ecosystem services (covering a range of provisioning, regulating and cultural services) in order to link climate change impacts directly to human well-being. For this paper, a subset of 13 indictors covering the range of sectors and important ecosystem services has been analysed for the whole of Scotland and four catchment-based regions (southern, central, north-eastern, Highlands and Islands—online resource 1):

- Artificial surfaces—the percentage of each grid cell under urban/suburban land cover;
- People flooded in a 1 in 100-year event—the number of people flooded in each grid cell by a 1 in 100 year (1 % probability of exceedence) coastal or fluvial event;
- Food production—gridded production-weighted food production;
- Extensively farmed—the percentage of each grid cell under sheep and beef cattle farming;
- Intensively farmed—the percentage of each grid cell under arable or dairying;
- Unmanaged land—the percentage of each grid cell that is not under agriculture, forestry or urban land uses;

- Forest area—the percentage of each grid cell under managed and unmanaged forest;
- Intensity index—scoring land uses in the following order of intensity: Urban > Intensive > Extensive > Forest > Unmanaged land, the total score for a grid cell is compared with the baseline value to determine whether or not land use has intensified;
- Land-use diversity index—calculated as one minus the Shannon Index of diversity based on six land-use classes (Arable, Intensive grassland, Extensive grassland, Unmanaged, Forest and Urban). Areas with equal proportions score 0 and those which are 100 % a specific land-use score 1;
- Water availability—annual average water resource availability;
- Water Exploitation Index—the proportion of the annual available water in each catchment that is abstracted;
- Irrigation usage—average annual volume of irrigation usage;
- Biodiversity Vulnerability Index—a measure of the total number of species within each grid cell that lose or gain both suitable climate and habitat space compared to the baseline. It is based on a subgroup of 11 species that represent a cross section of Scottish species from different taxa, regions and habitats.

Changes in the mean values of each of the thirteen modelled indicators across Scotland and the four regions from the model runs with the six climate scenarios that span the likely climate uncertainty in the 2050s (Table 1) and the five socio-economic scenarios (baseline socio-economics plus the four CLIMSAVE socio-economic

Table 2 Minimum and maximum values of the mean change from baseline for the 2050s for the climate change scenarios combined with the baseline (2000–2010) socio-economics (6 simulations) or with the CLIMSAVE socio-economic scenarios (24 simulations)

Indicator	Climate change scenarios with the baseline socio-economics										Climate change and CLIMSAVE socio-economic scenarios									
	Scotland		Highlands and Islands		Southern		Central		North-east		Scotland		Highlands and Islands		Southern		Central		North-east	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Artificial surfaces (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	31.7	0.0	19.1	0.0	70.2	0.0	27.8	0.0	45.4
People flooded (%)	10.7	31.6	21.8	47.6	1.2	9.4	7.3	29.9	0.0	13.2	-2.3	63.3	7.6	72.4	-11.8	71.8	-4.5	55.9	-15.1	67.9
Food production (%)	28.7	130.7	78.5	178.1	-42.4	107.0	-36.8	119.7	36.3	130.2	-9.7	93.2	25.0	252.4	-83.6	21.9	-76.7	42.5	-31.2	141.3
Intensively farmed (%)	12.2	51.1	38.9	74.9	-60.0	19.1	-35.4	65.5	37.0	85.9	-54.4	46.1	-37.7	93.9	-93.5	-30.8	-81.5	38.3	-64.9	74.4
Extensively farmed (%)	6.1	37.1	-4.5	18.0	20.7	89.6	-7.1	87.3	-32.1	30.5	-60.6	62.7	-50.7	32.4	-60.6	108.3	-91.2	127.6	-64.8	99.9
Unmanaged land (%)	-0.3	0.4	-0.3	0.3	0.0	0.1	-0.2	1.4	-0.2	1.4	-0.4	51.9	-0.4	25.8	-0.3	227.3	-1.5	242.5	-0.4	93.8
Forest area (%)	-50.5	-37.1	-58.4	-32.7	-38.2	-27.0	-50.3	-24.4	-62.2	-36.8	-55.0	-9.4	-70.5	-15.3	-54.1	-3.6	-71.0	-2.1	-46.4	-1.4
Intensity index (−)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	-0.1	0.0	-0.1	0.0	-0.2	0.0	-0.1	0.1	-0.2	0.1
Land-use diversity (%)	0.0	47.0	0.0	12.0	0.0	78.0	0.0	139.0	0.0	63.0	0.0	223.0	0.0	58.0	0.0	395.0	2.0	601.0	0.0	319.0
Water availability (%)	-4.5	15.8	-4.2	19.1	-7.2	9.3	-6.1	13.4	-7.0	9.6	-4.5	15.8	-4.2	19.1	-7.2	9.3	-6.1	13.4	-7.0	9.6
Water exploitation index (%)	-8.4	23.4	-12.5	19.5	-7.9	68.0	-7.7	19.7	-7.5	30.6	-57.7	57.5	-61.9	34.5	-57.6	278.5	-57.7	54.6	-52.2	110.6
Irrigation usage (10³ m³/yr)	6.1	17.8	5.7	14.1	-6.6	12.9	0.5	15.9	13.9	39.3	-21.3	10.9	-28.3	9.0	-18.7	8.4	-15.4	14.1	-7.0	27.2
Biodiversity VI (−)	-0.40	-0.20	-0.40	-0.10	-0.30	-0.10	-0.30	0.0	-0.50	-0.30	-0.30	0.00	-0.30	-0.10	-0.20	0.00	-0.20	0.10	-0.40	0.00

Italicised cells show indicators where the minimum and maximum changes are in different directions, where this is not the case the direction of change may be seen as robust in the context of the scenarios

scenarios) and in the distribution of indicator values across the 3,472 land grid cells were assessed to evaluate the implications of uncertainty in climate and socio-economic change for the direction, magnitude and distribution of impacts.

Model results

To evaluate the importance of future socio-economic change to the impact range associated with climate change uncertainty, Table 2 shows the minimum and maximum average change in each indicator in the 2050s across the climate change uncertainty, under baseline (2000–2010) socio-economics and the CLIMSAVE socio-economic scenarios. Shaded cells in Table 2 show indicators where the minimum and maximum changes are in different directions. Figure 3 shows the changes in the distribution of the indicators under the range of climate and socio-economic scenarios. Most indicators are expressed as percentage change from the baseline, except for the biodiversity vulnerability index, irrigation usage and intensity index (which are relative to the baseline).

Impact uncertainty arising from climate change uncertainty only

With climate change imposed on the current (baseline) socio-economic conditions of Scotland, there is a confidence in the direction of average change across the climate uncertainty for most indicators at the national scale, with only water availability, water exploitation index and unmanaged land showing uncertainty in direction (Table 2). There is, however, considerable uncertainty in the direction of change for many of the indicators at the regional scale. The robust regional results, where there is agreement in the direction of average change of an indicator across the climate uncertainty, are that:

- Urban sector—there are no changes in artificial surfaces as climatic factors do not influence simulated urban development
- Coastal sector—the average number of people flooded in a 1 in 100-year event increases in all regions, with impacts increasing with warming. Regional changes are modest, but are locally significant, as reflected by the 99th percentile grid cell value increasing from 530 to 600 people, given the sparse population over wide areas
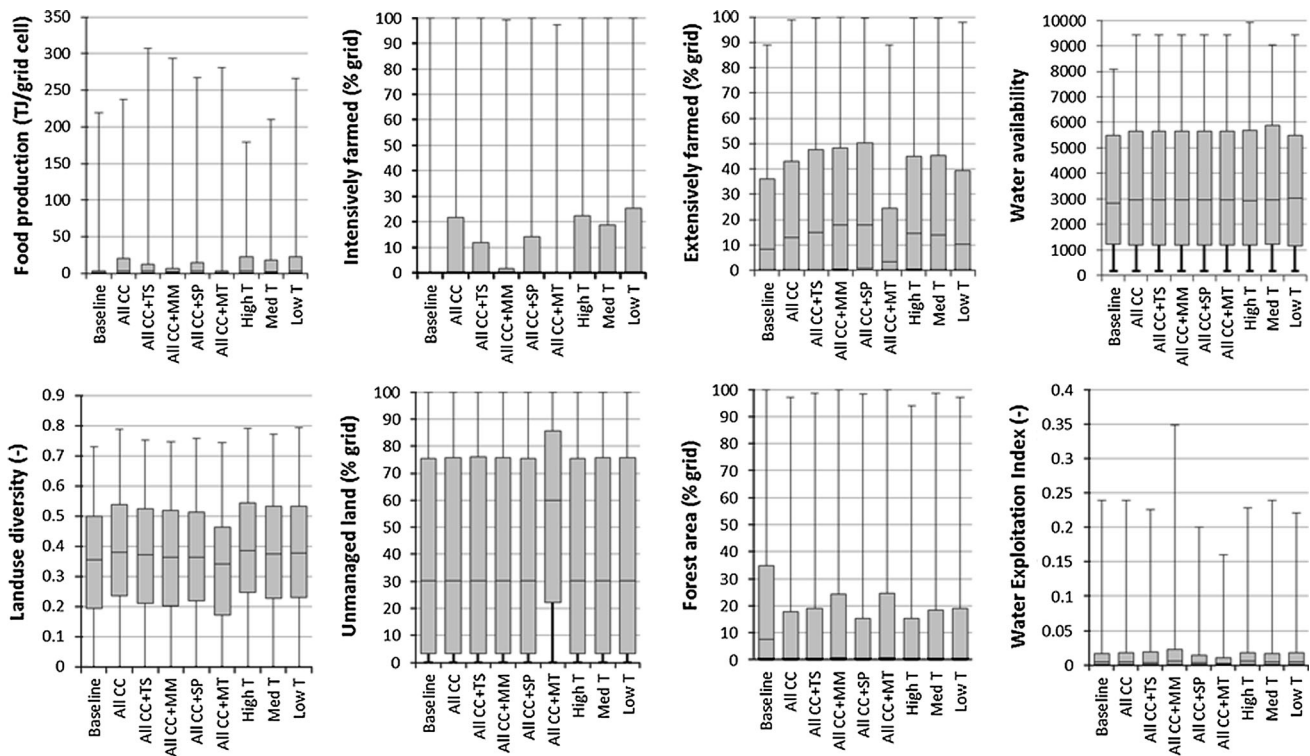
Fig. 3 *Box* and *whisker plots* for eight indicators for baseline, all 2050s climate with baseline (2000–2010) socio-economics (All CC) and the four CLIMSAVE socio-economic scenarios (+TS [Tartan Spring], MM [Mad Max], SP [Scottish Play], MT [MacTopia]) and for high, medium and low warming (with baseline socio-economics). The whiskers show the 1st and 99th percentiles whilst the *boxes* show the 25th and 75th percentiles. The median is marked with a *horizontal line* in the *centre of the box*

of Scotland. The largest absolute impacts are found in the more densely populated central region (which includes the cities of Glasgow and Edinburgh) and in the Highlands and Islands where much smaller dispersed population centres are generally located on the coasts and in river valleys. The increases largely reflect the relatively moderate increases in sea level by the 2050s (8–36 cm) under the climate change scenarios on coastal towns and cities.

- Land-use indicators: intensive farming increases by around 40–80 % in the north-east and Highlands and Islands, leading to an overall national increase of 10–50 %. As a consequence, food production also increases in the north-east and Highlands and Islands and nationally. The limited spatial extent of intensive agricultural land in Scotland results in the 75th percentile value increasing from 0 to 22 % intensive land in a grid cell and from 3 to 21 TJ/grid cell (Fig. 3). Extensive farming increases in southern Scotland and nationally, with the median proportion increasing from 9 to 13 % of a grid cell, with greater increases in the warmer scenarios. Forest area decreases across all regions of Scotland, resulting in changes in the median and 75th percentile coverage reducing from 191 to 0 ha/grid cell and 870 to 450 ha/grid cell, respectively. Unmanaged land shows little change in any region. The land-use model incorporates autonomous adaptation to ensure that sufficient food is produced to support the Scottish population, allowing for food imports. This focus on ensuring food provision has the cross-sector impact that, even in the absence of socio-economic scenarios, forest area declines often to be replaced by intensive or extensive agriculture.
- The land-use summary indicators reflect changes in land use with the intensity index showing no change or small increases across all regions of Scotland. However, there are significant localised changes, with the 1st and 99th percentiles changing by −0.23 and +0.4, respectively. The land-use diversity remains unchanged or increases nationally and in all regions representing an increase in the homogeneity of the landscape. Such reductions in the multi-functionality of the landscape are expected to reduce robustness to losses in the ecosystem services associated with any one land use.
- Water-related indicators: average irrigation usage increases in all regions but southern Scotland, most notably in north-east Scotland. This, however, occurs in the extremes of the distribution with the 99th percentile changing from 0 to 0.55×10^6 m^3/yr/grid cell.
- Biodiversity vulnerability index: this index decreases, indicating a reduction in vulnerability, in all regions of Scotland which reflects many of the selected species gaining climate space in the north-east and Highlands

and Islands as it gets warmer and sometimes wetter. Although there is no change in the median, the extreme values of the index decrease between the 25th and 1st percentiles, but there are local increases in vulnerability (with the 99th percentile increasing to 0.7, meaning that 70 % of species no longer have appropriate climate-habitat space) associated with localised losses of habitats and montane climate space.

Impact uncertainty arising from climate and socio-economic change uncertainty

With the uncertainty in future climate and socio-economic conditions, the increase in the number of italicised cells in Table 2 when the climate change scenarios are combined with the four CLIMSAVE socio-economic scenarios shows that there is increasing uncertainty in the direction of change at both the national and regional scales. The results that are robust in the direction of average change are as follows:

- Urban sector: area of artificial surfaces—the socio-economic scenarios generally lead to increases in the artificial surfaces associated with urban and rural development. The urban model is heavily driven by population and GDP changes. Therefore, socio-economic scenarios with high population increase and higher GDP, such as MacTopia and Tartan Spring, see the most growth. In contrast, the dystopian Mad Max scenario shows no trends >5 % at either the 25th or the 75th percentile due to the fact that both population and GDP are in decline.
- Coastal sector: the average number of people flooded in a 1 in 100-year event increases in the Highlands and Islands, but the range is greater than seen for the climate scenarios alone. There is no clear trend for southern, central or north-eastern Scotland. At the national scale for the majority of locations, there is very little change in the number of people flooded with a median of 0 in all scenarios. The indicator is largely driven by population and changes in the distribution of artificial surfaces. As a consequence, there are changes in the extreme values of the number of people affected by flooding that are consistent with the changes in population and urban development, with the greatest increase in the 99th percentile seen in MacTopia (where population increases by 34 %) and the lowest in Mad Max (where population declines by 11 %).
- Land-use indicators: the socio-economic scenarios make a significant difference to the patterns of intensive and extensive farming and unmanaged land across Scotland, considerably increasing the range of possible outcomes at national and regional scales: there is no

longer a clear direction of change for any region of Scotland with the exception of intensive farming in southern Scotland which shows general decreases. Food production only increases in the Highlands and Islands, whilst forest area decreases across all regions of Scotland compared to the baseline. However, there are differences in the extreme values of forestry, with Mad Max and MacTopia both leading to increases in the 75th percentile forest area compared to the effects of climate change alone. In scenarios such as The Scottish Play, where pressure is put on the food resource due to increasing population and a lack of resources, there are significant increases in overall food production that arise from expansion of extensive farming activity (the median increases from 13 to 18 %) at the expense of forestry, where the 75th percentile decreases from 447 ha/grid cell under climate change to only 380 ha/grid. There is little change in intensive farming and unmanaged land. Conversely, in scenarios where innovations are successful and high GDP growth allows increased food imports (such as MacTopia where food imports increase by 30 % relative to baseline), the median area of unmanaged land doubles at the expense of both intensive and extensive farming (Fig. 3).

- Land-use summary indicators: the socio-economic scenarios heavily influence the land-use intensity index and land-use diversity index. The average intensity index decreases in MacTopia in all regions and generally increases under the remaining scenarios in all regions, except southern Scotland. The changing patterns in land use also lead to impacts on land-use diversity—all regions decrease in diversity compared to the baseline due to the loss of forest area and changes to the distribution of unmanaged and agricultural land.
- Water-related indicators: there is no socio-economic influence on water availability. The socio-economic scenarios exacerbate the uncertainty in the direction of change in the water exploitation index and irrigation usage driven by climate alone in all regions, reflecting changes in both climate and socio-economic factors driving water extraction for agriculture, domestic/industrial use and power generation. In scenarios where societal breakdown and reducing wealth and resources lead to a loss of human and social capital (Mad Max), water consumption is higher leading to an increased water exploitation index (greater stress) and irrigation use is considerably lower in most regions. Conversely, the scenarios where human capital increases, enabling successful water-saving innovations or "living with less" (MacTopia and the Scottish Play), use increasing amounts of irrigation, whilst maintaining lower water

exploitation values in comparison with the impacts based on climate change alone.

- Biodiversity vulnerability index—the socio-economic scenarios partially offset the beneficial changes in the biodiversity vulnerability index driven by the changes in climate, although the average vulnerability index decreases (improves) nationally and in most regions. This reflects changes in habitat availability driven by a range of socio-economic factors which affect food demand and land-use change. The localised increases in biodiversity vulnerability generally increase with increasing temperature.

Discussion of model results and the CLIMSAVE participatory process

Adaptation strategies respond to the particular circumstances of potential future changes at regional and local scales, which arise from the interaction between the regional/local characteristics of climate variability and change and the inherent spatial variability in the structure and function of human and natural systems (Hibbard and Janetos 2013). Therefore, in common with many national and regional Governments in Europe and wider, the Scottish Government is developing a climate change adaptation programme, as a requirement of the Climate Change (Scotland) Act 2009. The draft programme's overarching aim is to increase the resilience of Scotland's people, environment and economy to the impacts of a changing climate (Scottish Government 2013). Draft objectives include improved understanding of impacts, supporting adaptive capacity, increasing awareness, sustaining and enhancing ecosystem goods and services and providing knowledge, skills and tools. These are all predicated on the availability of credible, transparent and relevant outputs addressing climate change impacts and adaptation, which can potentially be provided through participatory integrated assessments (Andersson et al. 2013), such as CLIMSAVE, and platforms, such as the CLIMSAVE IA Platform and Climate-Adapt.

However, there is significant spatial diversity in quantitative climate change impacts, and increasing uncertainty in the direction of change of impacts from national to regional scales associated with climate uncertainty. There is further increasing uncertainty associated with socio-economic change, such that the IA Platform identifies six indicators (artificial surfaces, biodiversity vulnerability index, forest area, intensity index, irrigation usage and land-use diversity) with robust directions of change at the national scale and only 3 (artificial surfaces, forest area and irrigation usage) that are robust in all regions (Table 2—as given by rows with no italicised cells). Given the great

uncertainty in the direction of impacts for many indicators due to future climate and socio-economic change at both national and regional scales, how are stakeholders to determine suitable adaptation responses?

One undesirable approach to dealing with such uncertainty found by Bormann et al. (2012) is for stakeholders to partly ignore uncertainty in model projections and to selectively use available information on expected climate change impacts to legitimise desired adaptation proposals. However, recognising that such uncertainty is a structural feature of complex problems (Wack 1985), the participatory process within CLIMSAVE and the IA Platform acknowledged that adaptation decisions cannot be made based on the "right" answer, but rather become a question of which options might work best in the face of contrasting possible futures. However, the use of conventional economic instruments such as cost-benefit models to make such prioritizations encounters difficulties when data are poor, future events are deeply uncertain or the attribution of benefits to interventions is confounded by multiple influences, which are typical characteristics of climate change projections acting on socio-environmental systems (Cartwright et al. 2013). Within the third of the CLIMSAVE Scottish stakeholder workshops, stakeholders worked in facilitated scenario groups to review potential adaptation options for their socio-economic scenario. The CLIMSAVE IA Platform was used within the workshop setting to initiate the discussion on the need for adaptation, through being used to simulate climate change impacts within their socio-economic scenario, and then to explore the efficacy of selected adaptation options within the IA Platform (including those associated with increasing food production, flood risk management, reducing water demand, changing dietary preferences for meat and increasing human and social capital). The Platform enabled a more nuanced exploration of the efficacy of scenario-specific adaptation policy options by the stakeholder groups, in particular because of the limits to adaptation imposed through the scenario assumptions and capital constraints. Based on the Platform results, augmented by discussion of adaptation options not included in the Platform, each group subsequently proposed a scenario-specific set of adaptation options and strategies.

A facilitated wind tunnelling session considered the practicality and efficacy of each of these scenario-specific policy options across all of the scenario storylines to identify adaptation policies or strategies that were robust to the uncertainty in socio-economic scenarios. However, given the uncertainty in both the magnitude and direction of many of the impacts of future change shown in Table 2 and the spatial variability across the country, the stakeholder groups characterised the resulting three robust adaptation policy options in Table 3 as those likely to be

beneficial to society (i.e. making the country a better place) in all scenarios, irrespective of the direction of change of the impacts, rather than necessarily being the optimum or no regret/low-regret solution across all scenarios (Gramberger et al. 2013). Their decision approach in the face of unavoidable uncertainty that became apparent through simulating climate change impacts across their scenarios within the participatory process was therefore to move away from a reliance on confidence in the prediction of climate change impacts towards valuing confidence in the ability to respond to a wide range of possible impacts (Cartwright et al. 2013). This adaptation decision paradigm, of moving away from seeking certainty towards beneficial solutions, is consistent with the view of Maslin (2013) that action on climate change should always contain an element of win–win, as society should not object to actions that create a better world, even if future climate change is at the low end of the projections.

The interactive and exploratory nature of Participatory IA platforms (such as the CLIMSAVE IA Platform; the Regional Impact Simulator—Holman et al. 2008; GB-QUEST—Carmichael et al. 2004) allows stakeholders to better develop their understanding of impacts and adaptation choices compared to the usual forms of the provision of study outputs, as they facilitate a deeper two-way iterative process of dialogue and exploration of "What if's". The use of the CLIMSAVE IA Platform within the CLIMSAVE participatory process conforms to many elements of the Diagnostic Adaptation Framework of Hinkel and Bisaro (2014). The Platform's Impacts screen was used by the stakeholders to assess the risks of climate change within their scenarios. They were able to identify potential adaptation measures within the workshops and use the Platform's Adaptation screen to appraise their options, taking account of the adaptive capacity constraints imposed by the scenarios and cross-sectoral unintended consequences, finally coming up with preferred robust options across the scenarios through consensus building. Based partly on their interaction within the CLIMSAVE IA Platform, climate change was not seen as the main driver of adaptation in Scotland, as the impacts (with the possible exception of extreme events) will be relatively benign, affording important opportunities. The original axis of uncertainty related to well-being and lifestyle together with building social cohesion and an equitable society was seen as the more important drivers of future adaptation and societal resilience, and highlights how the most efficient interventions across all futures and time frames tend to be socio-institutional (Cartwright et al. 2013).

The relationship between "choice, uncertainty and constraints" is a key cross-cutting theme in the conduct of past participatory integrated assessments (Salter et al. 2010). The integration in CLIMSAVE of a participatory

Table 3 Stakeholder identification of robust policy responses for Scotland in the 2050s (adapted from Gramberger et al. 2013)

Robust policy response	CLIMSAVE socio-economic scenario			
	Tartan spring	Mad max	The Scottish play	Mactopia
Investment in innovation	Innovation to drive and increase exports of agriculture and other natural resource-based products	Innovation is mainly linked to increasing agricultural exports	Innovation is not primarily technological, but relates to increasing human and social capital and linked to policy. Innovation is appropriate, cheap and delivered through focus on education	Innovation drives a shift towards green energy, green technology and new infrastructure. Innovation extends to social cohesion and governance, technological innovation in agricultural productivity and in maximising the benefits from water surpluses
Improved flood management	Flood protection and flood resilience measures protect the businesses of the wealthy	Flood defences to protect high-value crops and resources and affluent communities	Natural flood management as part of a multifunctional land-use strategy	People will move to make space for the water and new infrastructure will be built in less vulnerable spots
Best use of land	Land use is driven by the people who own it based on profitability ("Haves") and survival ("Have-nots")	Land use is driven by the people who own it based on profitability ("Haves") and survival ("Have-nots")	Sense of stewardship developed to promote equitable use, with eviction for poor management	Balancing the needs for energy, food and forests through multifunctional land use and innovation. Strong regulation and personal liability

scenario development process and an integrated modelling framework has allowed the exploration of future uncertainty in a structured approach. The interactive nature of the Platform, combined with transparent scenario settings, cross-sectoral interactions and adaptation limits, can expand and change the mental models of stakeholders (Gramberger et al. in press; Salter et al. 2010) and more strongly represent the importance of qualitative information and the social and institutional contexts within adaptation research (Hinkel and Bisaro 2014) and contribute to the development of better adaptation actions and policies across sectors.

Conclusions

The multi-sectoral indicators from the linked metamodels within the CLIMSAVE IA Platform show increasing uncertainty in the direction of change of future impacts from the national to regional scale in Scotland associated with the climate uncertainty within the probabilistic UK Climate Projections. The significant additional uncertainty associated with future socio-economic change results in only 6 (out of 13) indicators having a robust average direction of change across the scenario uncertainty at the national scale and only 3 that are robust across all regions. Such uncertainty in the direction, let alone magnitude, of future impacts for most indicators due to future climate and socio-economic change at both national and regional scales, precludes realistic identification of optimum or no regrets adaptation responses.

Consequently, the stakeholder groups identified three robust policy options (investment in innovation, best use of land and improved flood management) as those being beneficial to society in all scenarios, irrespective of the direction of change of future impacts. The study has demonstrated the benefits of integrating participatory scenario development processes (qualitative, bottom-up) and integrated modelling frameworks (quantitative, top-down), with the CLIMSAVE IA Platform providing a transparent interface between the qualitative stories and quantitative models that provided a more realistic representation of the

adaptation process within modelling, based on scenario-specific limits to adaptation. Together these enable the exploration of the uncertainty across diverse futures in a structured approach and the incorporation of the social and institutional contexts that frame and constrain adaptation in practice, which should inform the development of improved adaptation actions and policies across sectors.

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