Combining qualitative and quantitative understanding for exploring cross-sectoral climate change impacts, adaptation and vulnerability in Europe

Citation for published version:
Harrison, PA, Holman, IP, Cojocaru, G, Kok, K, Kontogianni, A, Metzger, MJ & Gramberger, M 2013, 'Combining qualitative and quantitative understanding for exploring cross-sectoral climate change impacts, adaptation and vulnerability in Europe' Regional Environmental Change, vol 13, no. 4, pp. 761-780. DOI: 10.1007/s10113-012-0361-y

Digital Object Identifier (DOI):
10.1007/s10113-012-0361-y

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
Regional Environmental Change

Reg Environ Change (2013) 13:761–780
DOI 10.1007/s10113-012-0361-y

ORIGINAL ARTICLE

Combining qualitative and quantitative understanding for exploring cross-sectoral climate change impacts, adaptation and vulnerability in Europe

Paula A. Harrison · Ian P. Holman · George Cojocaru · Kasper Kok · Areti Kontogianni · Marc J. Metzger · Marc Gramberger

Received: 13 January 2012 / Accepted: 4 October 2012 / Published online: 19 October 2012

Abstract Climate change will affect all sectors of society and the environment at all scales, ranging from the continental to the national and local. Decision-makers and other interested citizens need to be able to access reliable science-based information to help them respond to the risks of climate change impacts and assess opportunities for adaptation. Participatory integrated assessment (IA) tools combine knowledge from diverse scientific disciplines, take account of the value and importance of stakeholder 'lay insight' and facilitate a two-way iterative process of exploration of 'what if's' to enable decision-makers to test ideas and improve their understanding of the complex issues surrounding adaptation to climate change. This paper describes the conceptual design of a participatory IA tool, the CLIMSAVE IA Platform, based on a professionally facilitated stakeholder engagement process. The CLIMSAVE (climate change integrated methodology for cross-sectoral adaptation and vulnerability in Europe) Platform is a user-friendly, interactive web-based tool that allows stakeholders to assess climate change impacts and vulnerabilities for a range of sectors, including agriculture, forests, biodiversity, coasts, water resources and urban development. The linking of models for the different sectors enables stakeholders to see how their interactions could affect European landscape change. The relationship between choice, uncertainty and constraints is a key cross-cutting theme in the conduct of past participatory IA. Integrating scenario development processes with an interactive modelling platform is shown to allow the exploration of future uncertainty as a structural feature of such complex problems, encouraging stakeholders to explore adaptation choices within real-world constraints of future resource availability and environmental and institutional capacities, rather than seeking the 'right' answers.

Keywords Climate change impacts · Adaptation · Vulnerability · Integrated · Scenarios · Cross-sectoral

P. A. Harrison (✉)
Environmental Change Institute, University of Oxford,
South Parks Road, Oxford OX1 3QY, UK
e-mail: paharriso@aol.com
URL: www.eci.ox.ac.uk; www.climsave.eu

I. P. Holman
Cranfield Water Science Institute, Cranfield University,
Cranfield, Bedford MK43 0AL, UK

G. Cojocaru
TIAMASG Foundation, Sfintii Voievozi 6,
010963 Bucharest, Romania

K. Kok
Department of Environmental Sciences, Wageningen University,
P.O. Box 47, 6700 AA Wageningen, The Netherlands

A. Kontogianni
Laboratory of Applied Environmental Economics,
University of the Aegean, University Hill,
81100 Mytilini, Greece

M. J. Metzger
School of GeoSciences, The University of Edinburgh,
Drummond Street, Edinburgh EH8 9XP, UK

M. J. Metzger
ClimateXChange, 15 South College Street,
Edinburgh EH8 9AA, UK

M. Gramberger
Prospex bvba, Vlugestal 6, 3140 Keerbergen, Belgium

Introduction

In recent years, a consensus has emerged amongst a wide range of policy-makers and stakeholders that climate change is an increasingly important strategic, economic and political concern (Shackley and Deanwood 2002; Turnpenny et al. 2004; Holman et al. 2008; European Commission 2009). Decision-makers and other interested citizens now need reliable science-based information to help them respond to the risks of climate change impacts and assess opportunities for adaptation (Turnpenny et al. 2004). However, these impacts will be in addition to, or concurrent with, those associated with continuing socio-economic and political changes (Rounsevell and Metzger 2010). Our vulnerability to, and the potential impacts of, climate change therefore need to be evaluated in a holistic or integrated assessment of the effects of our changing future. Integrated assessment (IA), which is a structured process of dealing with complex issues using knowledge from various scientific disciplines and/or stakeholders such that integrated insights are made available to decision-makers (Rotmans 1998), provides an approach and a variety of tools and methods to develop the information resources required.

The first generation of IA models, developed in the 1970s and 1980s (see Hordijk and Kroeze 1997), focused on acid rain, which opened the way for applications linked to climate change (Van der Sluijs 2002). The first models focusing on climate change were developed during the early 1990s (e.g. Nordhaus 1994; Alcamo 1994). These models were eventually used to address questions related to the effectiveness of environmental policies at a global scale. More recent IA modelling has focused on its application at regional to local scales (Rotmans 2006) and has been accompanied by the introduction of participatory IA (PIA) methodologies (Van Asselt and Rijkens-Klomp 2002), which have become increasingly popular over the last decade (see Salter et al. 2010). However, despite recent advances, many IA-related projects continue to provide results or interpretations to stakeholders based on the outputs of particular simulations of an IA model. This is not sufficient to test the sensitivity of the human–environment system, to engender organisational or behavioural change or to enable knowledge creation as a learning process (Holman and Harman 2008). The focus has remained too much on a one-way flow of information from researchers to stakeholders, rather than a two-way iterative process of dialogue and exploration of 'what if's'. More interactive IA processes exist such as the story-and-simulation approach, where quantitative models and qualitative stakeholder products are linked, but these focus mostly on novel methods to conduct stakeholder workshops (e.g. Kok et al. 2011a; Sheppard et al. 2011). Very little attention has been paid to improving the way quantitative models are used. Most climate change IA models have unacceptably long run-times for allowing rapid simulation and interactive engagement with the IA. Alternatively, PIA platforms or interface-driven models (Salter et al. 2010) involving clear user interfaces, explicit recognition of uncertainty, and transparency in model performance and operation can take account of the value and importance of stakeholder 'lay insight' and promote dialogue between the research and stakeholder communities within a process of mutual learning and guidance (Turnpenny et al. 2004; Holman et al. 2008).

The EU CLIMSAVE project (www.climsave.eu) is developing a PIA platform that will allow users to explore and understand the interactions between climate change impacts in different sectors (agriculture, forests, biodiversity, coasts, water resources and urban development). This user-friendly web-based tool is being initially developed for Europe, but the software is also being tailored to the Scottish context, to test regional application of the approach. This paper describes the conceptual design of the CLIMSAVE Platform based on a professionally facilitated stakeholder engagement process which aims to ensure saliency and relevance of the platform. As part of this engagement process, a series of stakeholder workshops at the European and Scottish scales are providing information on the scenario storylines and the adaptation options to be included within the platform, as well as feedback on the interface design and functionality. The paper does not include detailed descriptions of all the individual model components of the CLIMSAVE Platform, for which reference is made to other reports and papers. Rather, the paper focuses on the holistic framework which underlies the Platform which has been designed to assist stakeholders in developing their capacity to understand the complex interactions between sectors in adapting to both climate and socio-economic change.

Policy context

Climate change adaptation is increasingly on the policy agenda in Europe. The key policy document for climate adaptation at the EU level is the White Paper on 'Adapting to climate change: Towards a European framework for action' (European Commission 2009). This sets out to provide a framework to reduce the EU's vulnerability to the impacts of climate change. The role of the EU is seen as supporting and strengthening actions taken at other levels of governance (national, regional and local) by establishing coordination and dissemination mechanisms for knowledge transfer to improve the effectiveness of adaptation, ensure solidarity amongst Member States and change policy in those sectors (such as agriculture and biodiversity) that are closely integrated through the single market and common policies (Pataki et al. 2011). A major initiative of the EU under the white paper has been to create a knowledge base for adaptation, the 'European Climate Adaptation Platform (CLIMATE-ADAPT)', that helps Member States to access and share information on expected climate change in Europe, the vulnerability of regions and sectors, national and transnational adaptation strategies, case studies of potential future adaptation options (including their costs and benefits) and tools that support adaptation planning. The CLIMSAVE IA Platform will form part of the tools provided by CLIMATE-ADAPT to support adaptation decision-making in Europe and a short movie introducing the functionality of the Platform was prepared for the launch of CLIMATE-ADAPT (http://climate-adapt.eea.europa.eu/climsave-tool).

In addition to the European IA Platform, a regional version of the platform is being developed to test the methodology at a lower scale. Scotland was chosen as the regional case study due to strong interest from stakeholders and because 2012 will be a key year in shaping Scottish adaptation policy. Adaptation policy in Scotland is devolved and the key legislation is the Climate Change Act (Scotland), which was passed in 2009. This sets greenhouse gas emissions targets, provides ministerial powers to create climate change duties on public bodies (Scottish Government 2011) and sets up the reporting infrastructure for measuring progress against mitigation and adaptation targets (Pataki et al. 2011). A Scottish Climate Change Adaptation Framework was published in 2009, with the intention to catalyse improvements with respect to adaptation and resilience (Scottish Government 2009). This was followed in 2010 with the publication of 12 sectoral action plans. The UK Climate Change Risk Assessment (CCRA), which is partly funded by the Scottish Government, has also produced a report on climate change risks in Scotland in 2012. The Climate Change Act (Scotland) requires the Scottish Government to draw up an Adaptation Programme to address the identified risks within this assessment. Furthermore, the Scottish Government has recently funded ClimateXChange (CXC),[1] a collaborative initiative between sixteen of Scotland's leading research and higher education institutions to deliver objective, independent, integrated and authoritative evidence to support the Government in relation to its activities on climate change mitigation, adaptation and the transition to a low carbon economy. The CLIMSAVE IA Platform will contribute to core CXC objectives by exploring potential impacts and adaptation strategies and identifying vulnerability hotspots. CXC has expressed an interest in further refining the IA Platform for Scotland as its work programme develops and would therefore be well placed to host the Scottish platform in the future. This would ensure that CXC and other users, for example, Scottish Natural Heritage, the Scottish Environmental Protection Agency (SEPA), the Forestry Commission and the Councils would have continued access beyond the lifespan of the CLIMSAVE research project. Alternatively, Scotland's Environment Web (SEweb), a knowledge base of public agencies aiming to help with the sharing of environmental information, could form a suitable host for the Platform. CLIMSAVE is in discussion with CXC and the SEPA to ensure full accessibility to potential Scottish users.

Stakeholder selection and engagement

In CLIMSAVE, the knowledge of stakeholders and scientists is highly integrated from the onset of the project. This integration calls for a systematic and continuous stakeholder engagement process (Kok and van Vliet 2011; Kok et al. 2011b). As part of this process, stakeholders have an active, driving role in developing and refining the qualitative socio-economic scenarios, the possible adaptation options and the link between both products. Finally, in collaboration with the scientists, these products are in turn linked to the CLIMSAVE IA Platform (Fig. 1). Stakeholders also provide feedback on the design and functionality of the user interface of the IA Platform through testing it. These aims are met by organising a series of professionally designed and facilitated workshops at each of the two scales. This will provide for an iterative exchange between stakeholders and scientists ensuring that stakeholder perspectives are an intrinsic part of the resulting scenarios. Stakeholders are thus mainly involved

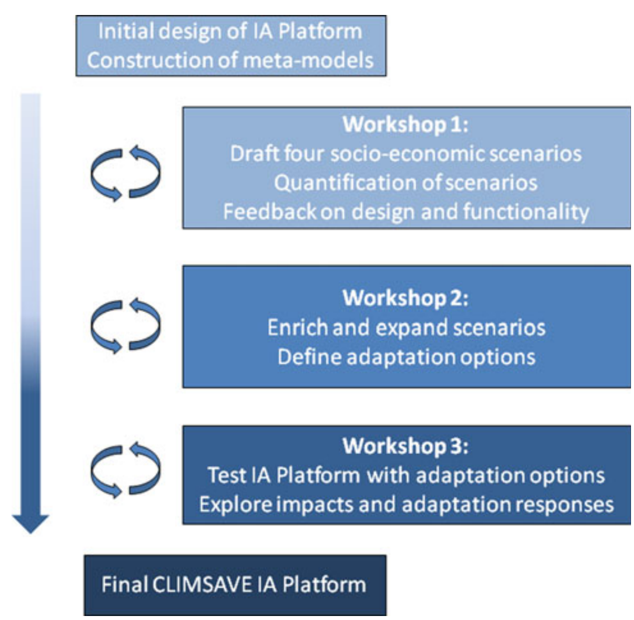

Fig. 1 The role of stakeholders within the CLIMSAVE process (colour online)

[1] http://www.climatexchange.org.uk/.

during a series of workshops. The subsequent sections will provide more detail on the design of the stakeholder selection process ('Stakeholder selection' section), provide some results from stakeholder questionnaires completed after the workshops ('Stakeholder satisfaction following the workshops' section), and a short description of the stakeholder-determined qualitative scenarios resulting from the workshops conducted so far ('Socio-economic scenarios' section).

Stakeholder selection

Design of the selection procedure

The importance of maximising the inclusion of a wide range of stakeholders' perspectives requires a careful and well-structured selection procedure. Stakeholder selection in CLIMSAVE is complicated by the fact that highly specific input by stakeholders through intensive and direct interaction is demanded, and by the fact that only 20–30 stakeholders can participate in each workshop due to budget constraints. The selection of individual stakeholders thus needs to be made with special care. The following categories were included in the procedure: (i) Social structure—governments, civil society, businesses, research; (ii) Geographical specificity—four regions in Europe and two regions in Scotland; (iii) Topical diversity—six sectors, including urban, agriculture, forestry, water, coasts and biodiversity; (iv) Gender balance; and (v) Age—four age groups. The same criteria for stakeholder selection from these categories were used for both the European and Scottish workshops. The aim is to maintain the same group of participants throughout the cycle of three workshops. This detailed process ensures that the project takes a conscious and planned approach to stakeholder identification and selection for participatory workshops.

Implementation of the selection procedure

The method of structurally identifying stakeholders helped to ensure a complete representation of stakeholders that needed to be invited. For example, the first European workshop covered the selection criteria as follows[2]: (i) Social structure—governments (10), civil society (7), businesses (7), research (4); (ii) Geographical specificity—northern Europe (3), southern Europe (6), western Europe (12), eastern Europe (5); (iii) Topical diversity—six sectors, including urban (15), agriculture (12), forestry (12), water (12), coasts (10) and biodiversity (14); (iv) Gender balance—women (10) and men (16); and (v) Age—20 to 30 years (1), 30 to 65 years (23), over 65 years (2). It also helped to increase the number of positive replies. However, it did not guarantee that there was a complete coverage amongst the stakeholders that actually participated which was particularly challenging for Europe where it was notably difficult to secure attendance by European government representatives. The attendance rate, however, was still relatively good, especially for the regional workshops, and participation by those stakeholders that did attend was very active in both sets of workshops. The method helped to identify those stakeholders that should be invited and subsequently those who did not participate, which is facilitating efforts for subsequent workshops.

[2] Some stakeholders covered more than one category of social structure and topical diversity. Data refer to the 26 stakeholders who accepted the invitation to attend the workshop.

Stakeholder satisfaction following the workshops

At the time of writing, two workshops have been carried out at the European scale and two at the Scottish scale. Stakeholder engagement in both sets of workshops conducted to date was successful. This is reflected by an overall high level of satisfaction specified in the evaluation forms from each workshop, illustrated by remarks such as: 'Excellent and very informative'; 'Engaging and thought provoking'; 'Very interesting process. Looking forward to how this develops'; 'Process worked well according to the high diversity of participants'; and 'I really enjoyed the experience. Curious to see the final products'.

Nevertheless, it has proven easier to recruit stakeholders and sustain their return to subsequent workshops in Scotland than in Europe. For stakeholders, it seems easier to identify with a region, such as Scotland, than with Europe partly because the attribution of European policy is seen as less direct. The link between climate change adaptation and stakeholder's own work is also clearer for the Scottish stakeholders. In addition, it is also easier for the Scottish stakeholders to join the event, since it involves less travel time and thus less time investment. These insights will be further elaborated using a stakeholder questionnaire after the third and final workshop to ascertain stakeholder's perceptions of the credibility and legitimacy of the workshop process.

Results from the workshops undertaken to date relating to the socio-economic scenarios that the stakeholder's developed are described in 'Socio-economic scenarios' section, whilst stakeholder's input on the interface design is encompassed in the list of design concepts and design functionality presented in 'Design of the user interface' section. In the final workshops, stakeholders will explore sets of strategic options and their consequences for climate change adaptation under the different scenarios by using the IA Platform (see 'Socio-economic scenarios' section). The final workshop will also conclude with overall lessons learned on both strategies for climate change adaptation under different scenarios and the social learning experience of the stakeholders involved.

Scenarios

Scenarios come in many shapes and forms. Several good review papers exist in which it is attempted to classify scenarios. For example, Van Notten et al. (2001) use no less than 14 characteristics to typify scenarios. In CLIMSAVE, the scenario process has four stages of development and/or utilisation. These are listed below, classified according to four criteria: (1) whether they are qualitative or quantitative; (2) whether they are explorative or normative; (3) whether they consider climate only or integrated biophysical and socio-economic variables; and (4) whether their development is led by scientific experts, stakeholders or both:

1. Socio-economic stories (qualitative, explorative, integrated, stakeholder-driven);
2. Climate scenarios (quantitative, explorative, climate, expert-driven);
3. Socio-economic and climate scenarios within the IA Platform (quantitative, explorative, integrated, both expert and stakeholder-driven);
4. Adaptation options within the socio-economic stories and IA Platform (qualitative and quantitative, normative, integrated, both stakeholder and expert-driven).

The overall scenario development method in CLIMSAVE closely follows the so-called story-and-simulation (SAS) approach in which narrative stories are developed and linked to mathematical models in an iterative procedure (Kok et al. 2011a, c). Essential in the SAS approach is the notion that the socio-economic stories that form the context for the modelling efforts are developed by stakeholders. These stories will then largely determine some of the important drivers of future change (e.g. population and GDP growth) that form the quantitative input for the mathematical models within the IA Platform.

This also closely resembles the latest efforts of the climate change community (led by the IPCC WGII and WGIII) to develop a new set of scenarios for the fifth assessment report. There is almost a complete analogy between the SAS approach and the approach taken by the climate change community as well as a strong resemblance between the four categories listed above and their Shared Socio-economic Pathways; Climate models, IA models, and Shared Climate Policy Assumptions. Note, however, that the IPCC-driven scenarios are global and therefore rely on (IPCC) expert opinions rather than on a broad stakeholder involvement.

Socio-economic scenarios

Crucial in the SAS approach is the development of qualitative (socio-economic) stories and quantitative models in an iterative manner. Socio-economic qualitative scenarios are developed over a series of three stakeholder workshops at each scale (see 'Stakeholder selection and engagement' section). Iteration will ensure a high level of consistency between the stakeholder-led qualitative socio-economic stories and the joint expert/stakeholder-led quantitative socio-economic scenarios, such that the expert-determined quantitative model outputs are representative of the stakeholders' stories. As such, the scenarios as developed by stakeholders determine the scenarios that are incorporated into the IA Platform.

At the time of writing, the first two sets of stakeholder workshops have been completed as discussed in the 'Stakeholder selection and engagement' section. The first workshops aimed at the development of three main products, namely (1) socio-economic qualitative scenarios; (2) quantitative estimates of key driving forces; and (3) lists of possible adaptation options. Elements included drafting a list of main uncertainties facing the EU/Scotland, selecting two key uncertainties that form the basis for four scenarios, drafting four stories and quantifying a number of model parameters using the fuzzy set method. For Europe, the two main uncertainties identified by the stakeholders were whether economic development was gradual or rollercoaster and whether innovation was effective or not (Fig. 2a; Gramberger et al. 2011a). For Scotland, the two main uncertainties were whether well-being and lifestyle were equitably distributed across society and whether natural resources were in surplus or deficit (Fig. 2b; Gramberger et al. 2011b). In addition to defining the structure of the scenarios, stakeholders also provided important information on the scenario elements and scenario dynamics associated with their storyline as well as quantifying seven key model variables (GDP, population, protected areas for nature, food import ratio, arable land used for biofuels, oil price and household size) using the fuzzy sets approach (Dubrovsky et al. 2011). Qualitative products provide important information on crucial uncertainties such as economic development, technological efficiency of solutions, and resource availability. The results from both the narrative stories and quantification exercise were used to estimate representative values for a wide range of socio-economic variables that are needed as inputs to the models within the IA Platform, for example, irrigation efficiency, water use intensity and electricity production. All these products were enriched and expanded during the second set of workshops where stakeholders also defined adaptation options that would be important for each of the scenario storylines. In the third and final set of

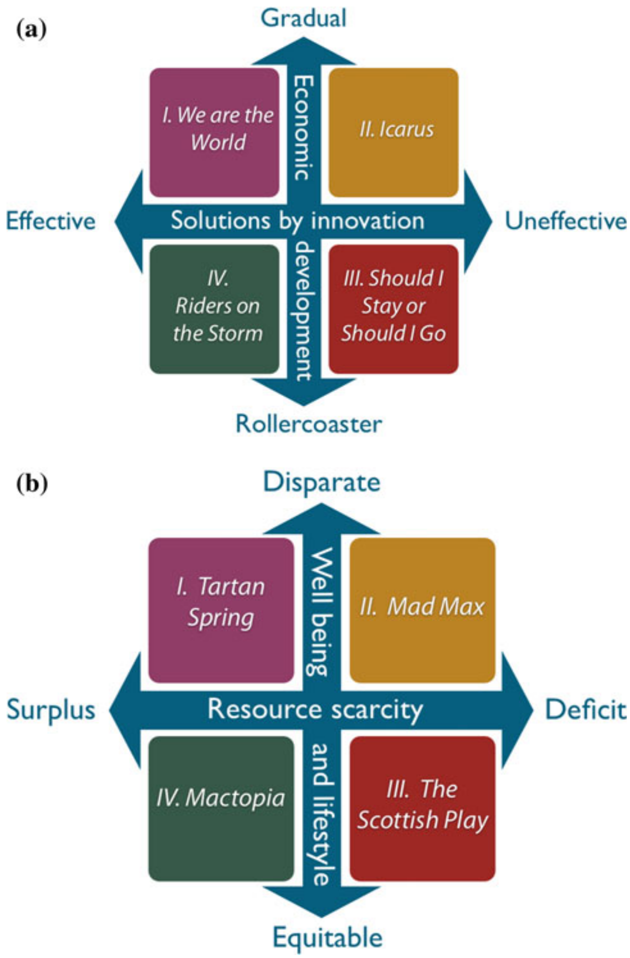

Fig. 2 The four socio-economic scenarios produced from the two sets of stakeholder workshops: **a** Europe; and **b** Scotland. *Source:* Gramberger et al. (2011a, b) (colour online)

workshops, stakeholders will have the opportunity to test the IA Platform and explore the effectiveness of different adaptation options in reducing climate change impacts and vulnerability under the socio-economic scenarios they have created.

Climate scenarios

In addition to socio-economic scenarios, a range of climate change scenarios have also been prepared as inputs to the models within the IA Platform. The user interface to the European IA Platform allows the user to select a SRES emissions scenario (A1b, A2, B1 or B2), the climate sensitivity (low, medium or high, with medium being the default) and the global climate model (GCM) in order to explore the effects of climate change uncertainties on cross-sectoral impacts and vulnerabilities. In order to make the number of combinations manageable for the user, it was decided to include five GCMs within the IA Platform out of the 16 available from the IPCC-AR4 database (http://www.mad.zmaw.de/IPCC_DDC/html/SRES_AR4/index.html). Thus, a methodology was developed to objectively select a representative subset of GCMs incorporating the 'best' GCM (through an assessment of GCM quality, based on the fit between model and observed annual cycles of precipitation and temperature), the most 'central' GCM (the GCM whose climate change scenario is the closest to the mean scenario over all 16 GCMs), and three other GCMs that preserve as much uncertainty as possible due to between-GCM differences (based on the Euclidean distance in an 8-dimensional space consisting of seasonal changes of precipitation and temperature) (Dubrovsky et al. 2011). The final set of GCMs selected to include in the IA Platform was MPEH5 ('best'), CSMK3 ('central'), and HADGEM, GFCM21 and IPCM4 (the triplet of most diverse GCMs for Europe).

The Scottish IA Platform incorporates climate change scenarios based on the UKCP09 scenarios (Murphy et al. 2009) as these provide projections of climate change for the United Kingdom with which the Scottish stakeholders are familiar and which give greater spatial and temporal details for Scotland than the GCMs from the IPCC-AR4 database. The UKCP09 scenarios are probabilistic projections 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. They are also available for three SRES emissions scenarios (A1FI, A1b and B1). In order to ensure an acceptable speed of operation of the platform as well as making the number of scenarios manageable, internally consistent scenarios were developed based on the 10th, 50th and 90th percentiles of average annual temperature and winter and summer half-year precipitation based on guidance from UKCIP (Roger Street, personal communication 2011).

The IA Platform

The CLIMSAVE IA Platform is an interactive exploratory web-based tool to enable a wide range of professional, academic and governmental stakeholders to improve their understanding surrounding impacts, adaptation responses and vulnerability under uncertain futures. The tool provides sectoral and cross-sectoral insights within a facilitating, rather than predictive or prescriptive, software environment to inform understanding of the complex issues surrounding adaptation to climate change. The power of the tool lies in its holistic framework (cross-sectoral, climate *and* socio-economic change) and it is intended to complement, rather than replace, the use of more detailed sectoral tools used by sectoral professionals and academics. As such, the IA Platform is not intended to provide detailed local predictions, but to assist stakeholders in developing their capacity to address regional/national/EU scale issues surrounding climate change. The Platform is also expected to be a valuable teaching tool which contributes to a better adapted Europe through assisting the intellectual development of future decision-makers. This vision of the use of the CLIMSAVE IA Platform is consistent with the recognition that the outputs from policy assessments are generally not carefully considered or used directly by decision-makers, but that their impact occurs in more subtle and nuanced ways such as by facilitating group learning amongst stakeholders and providing 'ammunition' that can be used to persuade opponents (Owens 2005).

The broad range of target users that are consistent with our vision has three main implications for the IA Platform design. Firstly, that web-based access and interaction are likely to be more practicable and effective than software requiring installation on user's PCs. Secondly, high visibility within the web is needed to reach users, which will require both local hosting (i.e. on the CLIMSAVE website) and access through European (European Climate Adaptation Platform—Climate-ADAPT; www.climate-adapt.eea.europa.eu) and regional (e.g. ClimateXChange—CXC; www.climatexchange.org.uk or Scotland's Environment Web—SEweb; www.environment.scotland.gov.uk) portals. And finally, that the use of the final IA Platform by target users in both a supervised environment (e.g. the third set of CLIMSAVE stakeholder workshops facilitated by CLIMSAVE team members) and through free access via the Internet requires that the IA Platform design is as user-friendly and intuitive as possible.

The CLIMSAVE IA Platform is based on a web Client/Server architecture that uses both server-based (i.e. remote) and client-based (i.e. the user's PC) computing solutions on the web. The models and the underlying physical (soils, land use, etc.) and scenario (climate and socio-economic) datasets use server-based web technologies, as this avoids the need for input data to be transferred to the user's PC (and hence the requirement for the user to sign data licenses) and maximises access speed. The web-based interface for stakeholders has been developed using a client-based computing solution based on Microsoft Silverlight technology (a Rich Internet Application framework) as this allows: (1) fast reply to the user actions; (2) the output data from (server-based) models to be sent synchronously and asynchronously to the client-based interface, as output data from faster meta-models can be displayed by the user whilst other models finish their run to give the impression of a real-time response; and (3) the opportunity to use map services (e.g. Google Earth, Bing Maps) to display spatial data.

Meta-model development

In order to provide an IA Platform with rapid interactively for the user, the run-times of the models on the server should be as short as possible. Hence, a meta-modelling approach is being used to deliver these fast run-times whereby computationally efficient or reduced-form models that emulate the performance of more complex models are being developed (Holman and Harrison 2011; Holman et al. 2008). Ten different meta-models have been 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 (Table 1). The meta-models are implemented as Dynamic-Link Libraries (DLL) developed in various software languages: Microsoft C++, Microsoft C#, Microsoft VB and Delphi as both managed and unmanaged code. They produce outputs on both sector-based impact indicators (covering agriculture, forests, biodiversity, coasts, water resources and urban development) and ecosystem services in order to link climate change impacts directly to human well-being (Table 2).

Linking the meta-models

For efficient development of the IA Platform, each of the computationally efficient meta-models is designed to be modular, independent and capable of replacement at any time. A meta-model specification has therefore been developed to ensure successful linkage of the models, irrespective of the final equations inside each of the models. The development of the specification has gone through five distinct stages:

1. Defining the spatial resolution of the data to be transferred between meta-models;
2. Identifying and prioritising meta-model inputs and outputs, based on the relevance for adaptation and for stakeholders (Table 2);
3. Identifying points of potential data transfer between the meta-models;
4. Specifying the data dictionaries, which define the inputs and outputs, for each meta-model;
5. Standardising the data dictionaries across all of the meta-models so that data can be passed between meta-models.

The spatial scale of the Platform represents a compromise between the scale of available harmonised datasets, model run-time and spatial detail of the outputs. The higher the resolution at which it operates, the greater is the number of times that the meta-models have to run and hence the greater the overall run-time of the Platform. The European and Scottish IA Platforms therefore operate at

Table 1 Details of the ten meta-models included within the IA Platform

Meta-model	Original model	Meta-modelling approach
Meta-RUG	Regional urban growth (RUG) (Reginster and Rounsevell 2006)	Look-up tables
Meta-crop yield (winter wheat and spring wheat, winter barley and spring barley, winter oil seed rape, potatoes, grain maize, sunflower, soybean, cotton, grass, olives)	ROIMPEL (Rounsevell et al. 2003; Audsley et al. 2008)	Soil/climate clustering combined with artificial neural networks
Meta-pest	CLIMEX (Sutherst et al. 2001)	Artificial neural networks
Meta-GOTILWA+	GOTILWA+ (Morales et al. 2005; Schröter et al. 2005)	Artificial neural networks
Meta-SFARMOD	SFARMOD (Holman et al. 2005; Annetts and Audsley 2002; Audsley 1981)	Soil/climate clustering combined with artificial neural networks
WaterGAP meta-model (WGMM)	Water—global assessment and prognosis (WaterGAP3) (Alcamo et al. 2003; Döll et al. 2003; Verzano 2009)	3-Dimensional surface response diagrams
Coastal fluvial flood meta-model (CFFlood)	RegIS2 (Mokrech et al. 2008; Richards et al. 2008) and DIVA (Vafeidis et al. 2008; McFadden et al. 2007)	Simplified process-based model
SPECIES	SPECIES (Pearson et al. 2002; Harrison et al. 2006)	Artificial neural networks
Meta-LPJ-GUESS	LPJ-GUESS (Sitch et al. 2003)	Look-up tables
Meta-SnowCover	SnowMAUS snow cover simulator (Trnka et al. 2010)	Artificial neural networks

For further information about the development, calibration and validation of the meta-models, see Holman and Harrison (2011)

resolutions of 10 arcmin × 10 arcmin (approximately 16 km x 16 km in Europe) and 5 km x 5 km, respectively, consistent with the available baseline climatologies.

Figure 3 shows a simplified flow diagram which highlights the linkages between the different sectoral models. For example, projections from the urban model on the location, area and type of urban development affect river basin hydrological responses, the population exposed to flood risk, the land available for agriculture and forestry and consequently habitat availability for biodiversity.

Design of the user interface

The CLIMSAVE IA Platform is designed to facilitate a two-way iterative process of dialogue and exploration of 'what if' questions through the development of an intuitive interface that should enable an interested individual to use the Platform with minimal recourse to help files and, importantly, without the need for training. Based upon the examination of other participatory model interfaces (e.g. the Regional Impact Simulator (Holman and Harman 2008; Holman et al. 2008), CLIMPACTS (Kenny et al. 2000), SimCLIM (Warrick et al. 2005), MULINO (Giupponi 2007; Giupponi et al. 2004), GB-QUEST (Carmichael et al. 2004), Climate Wizard (www.climatewizard.org/)) and potential user requirements, a list of design concepts and design functionality were identified for the user interface (Holman and Cojocaru 2010):

- The user should not need to go through an extensive or prolonged model set-up and the run-times should be as short as possible to prevent users getting bored and disengaging;
- The layout of the user interface should allow the user to understand potential sectoral and cross-sectoral impacts, evaluate the effects of adaptation on these potential impacts and to assess the cost-effectiveness of different adaptation measures;
- Tooltips should be used to provide on-screen user guidance;
- The user should be able to vary model input parameters within numerical ranges, rather than through qualitative descriptors of magnitude, to increase the transparency of the model/scenario assumptions (Schneider 1997);
- The user should be able to conduct sensitivity and uncertainty analyses, but guidance must be given to constrain 'realistic' ranges of values within scenarios and to account for uncertainty (Turnpenny et al. 2004);
- The user should be able to view model outputs as conventional impact indicators and as indicators of ecosystem services;
- The user should be able to view model outputs in a variety of forms, for example, maps, tables and graphs;
- The user should be able to view outputs at a range of scales of aggregation and zoom in, zoom out and pan across mapped model outputs within appropriate limits; and

Table 2 Output sectoral and ecosystem service indicators produced by the IA Platform

Sector	Sectoral output indicators	Ecosystem service indicators
Urban	Area of artificial surfaces	N/A
	Area of residential and non-residential areas	
Cropping	Crop yields (potential, nutrient-limited and nutrient and water-limited) for 10 crops	Food production delivered through the rural land use sector
Pests	Number of generations per season (6 species)	N/A
	Ecoclimatic index (quality of the ecoclimatic niche for 6 species)	
Forestry	Wood yield in managed forests	Timber production
		Carbon sequestration
		Water storage in soils
		Naturalness, tranquillity, isolation
Rural land use	Total crop production	Food production
	Biomass energy	Animal production
	Food energy	Bioenergy production
	Irrigation water demand	Fibre production
	Intensively and extensively farmed, forested and abandoned land	Irrigation use
		Attractiveness of agricultural landscapes
		Naturalness
Water	Naturalised high and average monthly river flow	Drinking water
	Water availability	Cooling water
	Water availability per capita	Water storage
	Real low, average and high flows	
	Water stress	
	Total water use	
Flooding	Area at risk of flooding	Flood protection
	Damages caused by flooding	
	People affected by flooding	
	People in flood risk zones	
	Areas of coastal grazing marsh, salt marsh, intertidal flats and inland marshes	
Biodiversity	Species presence/absence	Biomass production
	Species sensitivity indices	Wild food plants
	Net primary production (by plant functional type and species)	Pollination
	Biomass (by plant functional type and species)	Vegetation influence on local climate
		Attenuation of runoff
		Charismatic or iconic wildlife
		Species for hunting
		Attractiveness of forest landscapes
		Areas protected for nature

- The user should be able to export model outputs for subsequent analysis.

The IA Platform includes four screens: (1) impacts, (2) vulnerability, (3) adaptation and (4) cost-effectiveness. Figures 4 and 5 show the Impacts screen which attempts to embed these design principles. For example, a traffic light-based system of colour coding of the slider bars associated with the meta-model inputs is used to communicate the parameter uncertainty within a scenario; green denotes uncertainty that is 'credible' within the context of a scenario storyline (green for 'go'); yellow denotes wider uncertainty that may be possible, but which is outside of the considered wisdom for the scenario (yellow for 'caution'). For obvious reasons, a user is not permitted to enter a red, or 'no go' zone.

Future application of the IA Platform

This paper describes the conceptual design of the CLIMSAVE IA Platform and its integration within an ongoing

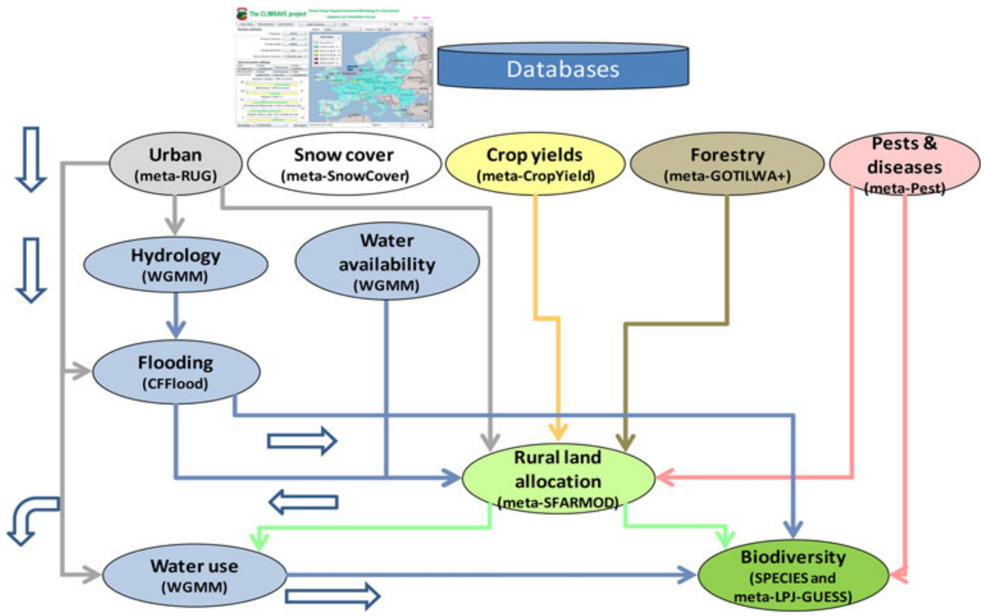

Fig. 3 Simplified schematic showing data transfers between meta-models in the CLIMSAVE IA Platform (colour online)

stakeholder engagement process which ensures consistent socio-economic scenarios and model assumptions. Given the iterative nature of the development process, we expect the user interface to undergo further modifications and refinements in response to progressive stakeholder feedback. However, the underlying meta-model structure and linkages will not alter greatly from that reported here. The tool will allow stakeholders to undertake rapid simulations of cross-sectoral impacts and to explore adaptation strategies for reducing climate change vulnerability.

We anticipate that users will come from a broad community. At one level, these may be the policy-makers at EU, national and regional levels who are the target audience for the European Climate Adaptation Platform (CLIMATE-ADAPT) and who are represented by the demographic which participated within the CLIMSAVE stakeholder workshops. At the other end of the spectrum, it is envisaged that the CLIMSAVE IA Platform will be extensively used as a teaching tool in a similar manner to the Regional Impact Simulator (Holman and Harman 2008; Holman et al. 2008). However, in both cases, it is anticipated that the IA Platform will primarily facilitate users in exploring the complex inter-sectoral issues associated with climate impacts, adaptation and vulnerability, that will ultimately lead to a better adapted Europe through enhancing the adaptive capacity of current and future decision-makers. In doing this, this section provides a brief overview of the types of analyses that could be undertaken using the final IA Platform.

Assessment of impacts and vulnerability

The sensitivity of the different sectors and ecosystem services to changes in both key climate and socio-economic variables can be assessed through altering a wide range of model inputs covering five categories: social, technological, economic, environmental and policy (Fig. 4). The upper and lower numerical limits on the slider bar for each model input have been determined through an assessment of the range of values over which each meta-model gives reliable outputs. This allows the user to gain confidence in the performance of the meta-models within the platform and to identify drivers of change which are particularly important for different sectors or cross-sectoral interactions. The IA Platform can then be used to investigate whether different climate and socio-economic scenarios have a negative or positive effect on different sectors or ecosystem services in two time slices (the 2020s and 2050s), including the evaluation of cross-sectoral benefits, conflicts and trade-offs (Fig. 5). Default values for the socio-economic inputs to the meta-models consistent with the scenario storylines developed within the stakeholder workshops have been defined. However, users have the flexibility to alter these values within a credible range that is consistent with the underlying socio-economic story (coloured green on the sliders shown in Fig. 5) or outside of this credible range (coloured yellow in Fig. 5) to investigate uncertainty or if they do not agree with the defined credible range or want to create their own socio-economic scenario. In this latter case, the outputs are labelled as a user-defined scenario rather than one of the predefined scenarios.

Vulnerability is computed as a function of the magnitude of the drivers or pressures of change (exposure; represented through the scenarios), the sensitivity of the system to these drivers (as given by the changes in the outputs from the linked meta-models) and the capacity of

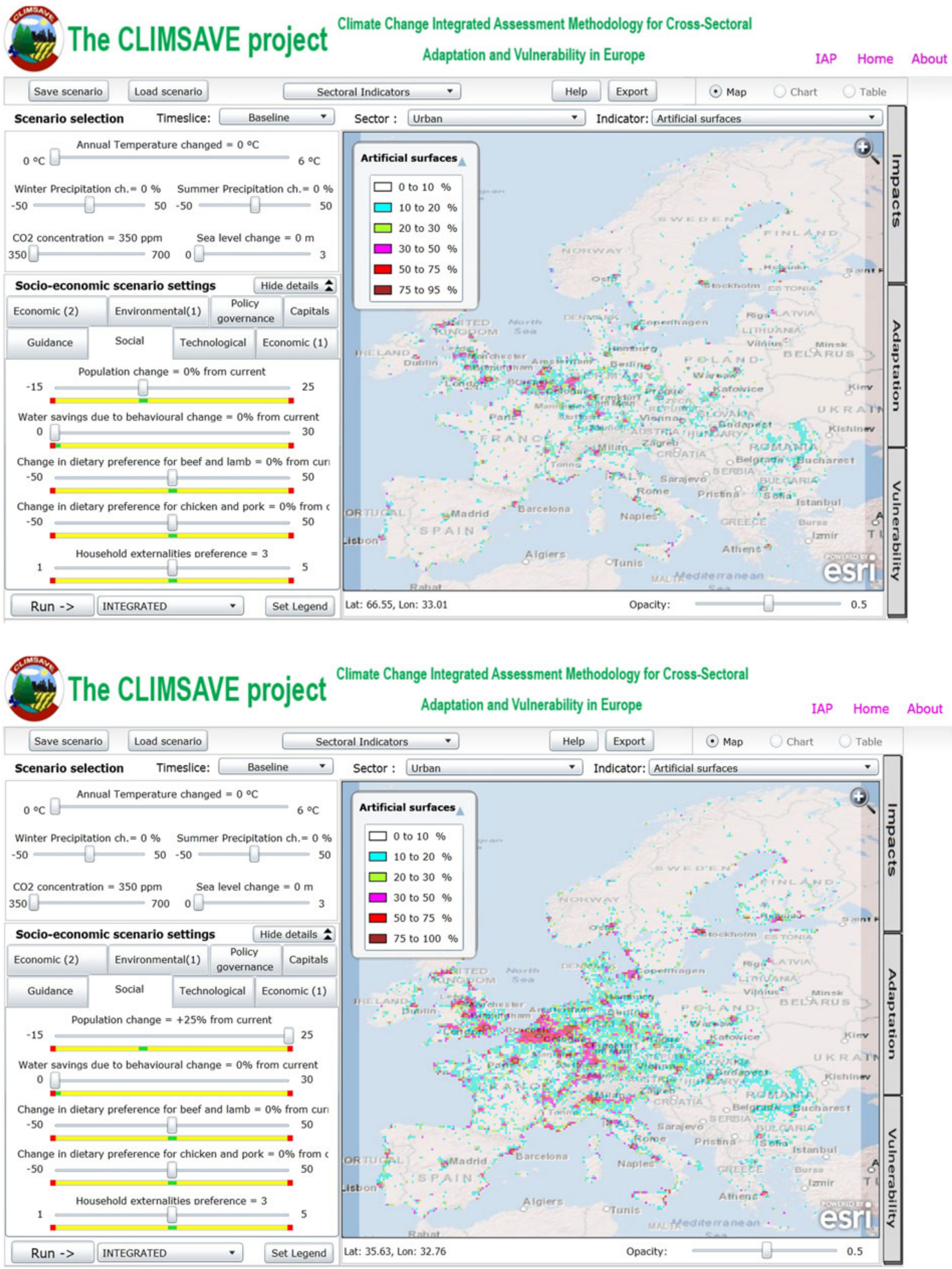

Fig. 4 The user interface of the European IA Platform showing the "Impacts" screen. The figure shows an illustration of using the IA Platform to undertake a sensitivity analysis for the percentage of artificial surface for the (*upper*) default baseline and (*lower*) with a population increase of 25 % and a GDP change of +200 %

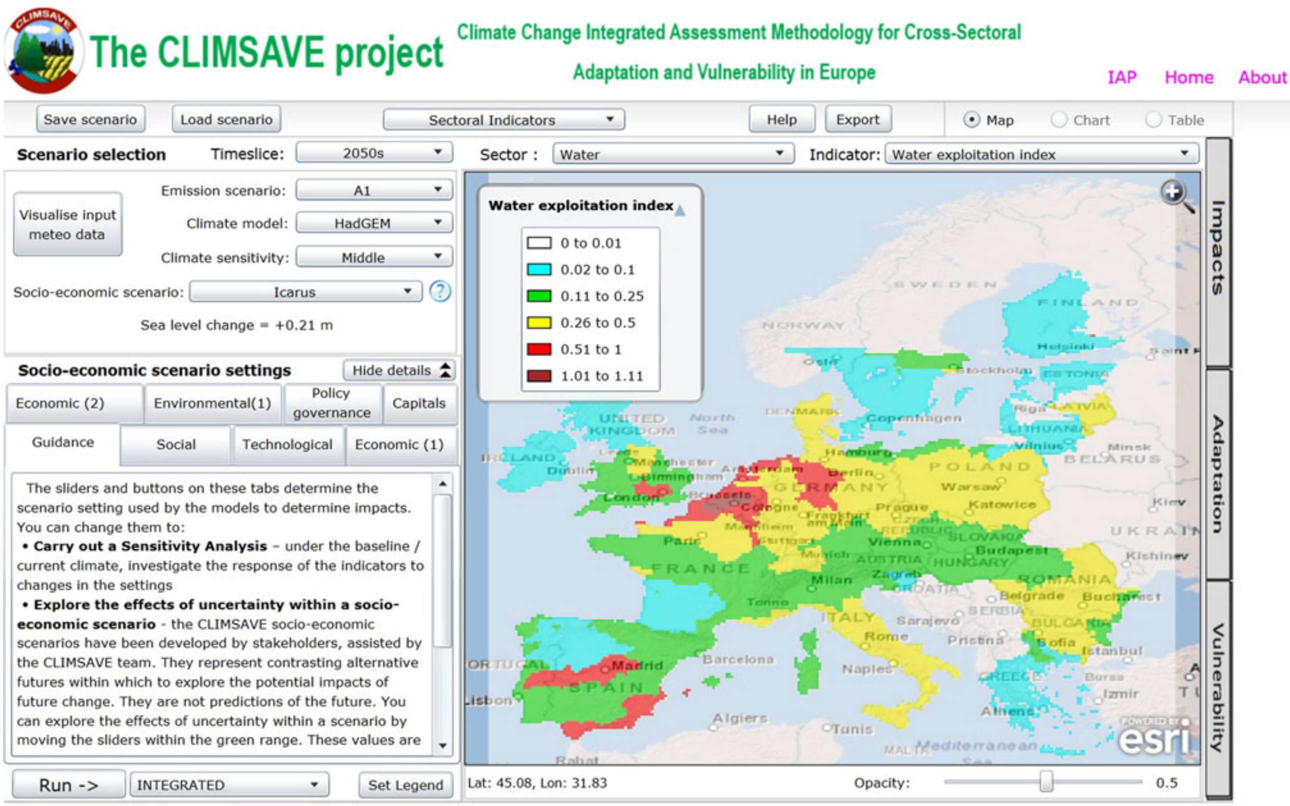

Fig. 5 The user interface of the European IA Platform showing the 'Impacts' screen. The figure shows an illustration of using the IA Platform to undertake a scenario analysis for the water exploitation index (based on the withdrawal-to-availability ratio) for an IPCC AR4 climate change scenario (A1 SRES scenario, HadGEM climate model and high climate sensitivity) and a CLIMSAVE socio-economic change scenario (Icarus) for the 2050s time slice

people to cope with these effects (represented by coping capacity). Coping capacity depends on the amount of capital (human, social, natural, manufactured and financial) that can be deployed quickly to cope with exposure to pressures and a coping capacity index is calculated from a range of indicators representing these five capitals (Omann et al. 2010; Tinch et al. 2011). If the value of the ecosystem service or sectoral indicator (in a specific time slice) is greater than a predefined tolerance level and there is insufficient coping capacity, then the potential impact is deemed unavoidable and vulnerability occurs. The tolerance level at which a potential impact is defined may represent physical limits (e.g. the height of a flood defence dyke) or mandated limits, for example, the concentration of nitrates allowed in drinking water. Vulnerability hotspots can be viewed on maps which allow a user to explore vulnerability for a single ecosystem service or sectoral indicator or for various combinations of indicators which represent aggregated vulnerability across multiple ecosystem services or sectors.

Assessment of adaptation options and their cost-effectiveness

After investigating potential sectoral and cross-sectoral impacts under a range of scenarios, stakeholders can explore adaptation strategies for reducing climate change vulnerability, discovering where, when and under what circumstances such actions may help. Adaptation can act on the drivers and pressures to reduce the value of an impact in order to stop a tolerance level being reached or by increasing the coping capacity of society. An example of the former is the introduction of stricter land use planning policy to restrict urban expansion (e.g. through green belts), or the introduction of crop irrigation in response to drought. An example of the latter is increasing the height of flood defences in adapting to sea level rise. Adaptation options that can be represented in the platform are obviously limited to those that can be linked to a parameter in one or more of the meta-models. These 'broad adaptation sliders' are shown in Table 3, along with examples of

Table 3 Broad adaptation options ('sliders') in the CLIMSAVE IA Platform and examples of specific actions for their implementation

Broad adaptation options	Related specific actions
Spatial planning for urban sprawl: Planning policy to control urban expansion, and so protect land availability for food and biodiversity	Planning restrictions on greenfield developments Minimum density requirements for new schemes Measures to force housing stock into greater use, for example, tax on empty properties, tax on second homes, tax breaks or regulatory relaxation on letting parts of properties
Spatial planning for coastal development: Discouraging coastal development to reduce exposure to coastal flooding	Planning controls on development within coastal floodplain Availability of flood insurance
Preference for rural living: Reflects people's relative desire to live in rural areas with access to green space or urban areas with access to social facilities	Consumer demand for green infrastructure Market plus policy measures Influencing preferences (e.g. investments in promoting outdoor activities, health education)
Flood protection upgrade: Improving the standard of flood defences	Building/maintaining flood defences Improving defence heights
Flood resilience measures: Changes to reduce the amount of damage caused by a flood	Improvements to housing stock Development planning Retro-fitting Early warning systems Evacuation plans
Water technological change: Using technology to reduce industrial and domestic water demand	Technological improvements in white goods efficiency Investments in leak reduction Industrial process use efficiency Pricing policy
Water structural change: Promoting behavioural change to use less water	Education and training Water pricing Hosepipe bans
Water demand prioritization: How water should be prioritised when demand is greater than availability (food, environment, domestic and industrial)	Abstraction management and regulatory control
Irrigation water cost: Changing irrigation water price to change water use efficiency and demand.	Irrigation price
Irrigation efficiency: Changing the amount of water used to produce a fixed amount of food	Investment in more efficient irrigation methods Crop breeding
Yield improvement: Change in yields, due to plant breeding and agronomy (leading to increases) or environmental priorities (leading to decreases)	Conventional crop breeding GM crops Increased agrochemical use Switch to organic farming
Change in food imports: To encourage food self-sufficiency but reduce European land availability for biodiversity, or increase imports but make Europe more vulnerable to external crop failures	Trade policy to restrict imports Domestic policy to encourage production Change agricultural support—more set-aside; more abandonment
Change in bioenergy production: Represents more land allocated to agricultural bioenergy and biomass crops (and so less for food and nature) or vice versa	Policy—non-fossil fuel requirements (biodiesel, etc.) Regional development programme support
Change in dietary preference for beef/lamb and chicken/pork: Reducing meat consumption in response to anticipated food shortages	Education/promotion of healthy lifestyles Pricing policy, direct via tax on meat Pricing policy, indirect via taxes on animal emissions Changes to agricultural support payments Rationing
Reducing diffuse source pollution from agriculture: Changing agricultural practices to reduce water pollution	Fertiliser/pesticide tax Fertiliser restrictions (e.g. nitrate vulnerable zones)

Table 3 continued

Broad adaptation options	Related specific actions
Set-aside: Represents the percentage of land removed from production for environmental benefits or to regulate production	Implementing set-aside Agri-environment options (e.g. buffer strip)
Forest management: Changing forest management practices—from intensive management for timber production with lower nature and recreation values, through to lower intensity management with good nature and recreation/cultural values and reasonable timber production	Changing forest management practices
Tree species: Planting tree species which are better suited to the changed climate	Planting new species
Wetland creation: Represents managed realignment where flood defences are moved inland to make space for creating coastal wetlands	Managed realignment
Habitat creation options: Increasing the size of existing protected areas (PA), so as to improve the ability of species to cope with change; or increasing the number of PAs, so as to fill gaps in the PA network and to improve species' movements across the landscape	Designation Land purchase (voluntary) Land purchase (compulsory) Agri-environment schemes

specific actions/measures that could be used to implement them. Users can select adaptation options either individually or in combination and examine the effect of the option(s) on impacts and vulnerability. Iteration of this approach can be used to explore the effects of different selections of adaptation options and uncertainties, determine the adaptive capacity of the system and optimise adaptation strategies.

Each adaptation option has certain requirements (e.g. costs, skills and/or technologies) that may not be available in all socio-economic scenarios. Further, these requirements are cumulative and so choice of some adaptation options may 'use up' the capacity needed to take further adaptation options. This is taken into account in the platform by using the indicators of the five capitals to limit the 'credible' range of adaptation options such that it is consistent with the socio-economic scenario under consideration. These constraints are indicative but not binding, in order to maintain maximum flexibility for platform users.

A separate cost-effectiveness screen in the IA Platform provides information on the least-cost alternative out of all the specific adaptation measures that could be associated with a user-defined desired level of adaptation (Table 3; Skourtos et al. 2011; DEFRA 2008). Synergistic and/or antagonistic effects between available measures and across sectors are taken into account in the calculation of cost-effectiveness either directly (i.e. when ancillary costs and benefits are quantifiable) or indirectly (i.e. on the basis of a suitable weighting scheme) (Klein et al. 2005). Expected effectiveness in addressing climate change impacts is assigned to individual adaptation investments on the basis of engineering data. A cost-effectiveness analysis algorithm computes the unitary, financial costs in achieving the specified target for each adaptation measure or combination of measures. Cost estimates are being collected and homogenized in a suitably structured database and are normalized (or 'weighted') in order to control for inflation and wealth effects where possible. This is then used to calculate the total implementation cost which depends on the extent of implementation for each combination of measures separately. Finally, the cost-effectiveness ratio is defined and used to rank all possible combinations so as to identify the least-cost combination. The user can vary the implementation time for each measure and the default values for discount rate, expected effectiveness and unit cost within the analysis. The analysis can also be rerun if desired using different methods for quantifying uncertainties in the cost estimates (variation analysis, fuzzy sets, Monte Carlo simulations, log-normal analysis and extreme cases analysis) (CCSP 2009) and the user can examine how these affect the ranking of the cost-effectiveness ratios (Skourtos et al. 2011).

Illustrative results for Europe

The strength of the CLIMSAVE IA Platform is the rapid interactivity that allows the user to quickly explore different climate and socio-economic scenarios, uncertainty in the scenario settings and inter-relationships between sectors. To illustrate this, the European IA Platform has been used to explore the effects of two of the CLIMSAVE socio-economic scenarios ('We Are The World' and 'Should I Stay or Should I Go'—Fig. 2) within the 2050s on urbanisation, land use and total water use, using the HadGEM climate scenario under an A1 emissions scenario and with medium climate sensitivity.

The simulated baseline depicts the high level of urbanisation in northwest Europe (Fig. 6), with major cities evident where more than 50 % of the surface area is residential or non-residential development. Under the 'We Are The World' socio-economic scenario, there is a no change in the extent of the major urbanised areas such as London, but an urbanisation of rural areas as increasing affluence and successful technological innovation leads to migration into the countryside. In contrast, the increasing societal inequality, greatly reduced GDP and increased population within 'Should I Stay or Should I Go' lead to migration from rural areas into the existing housing stock of the cities.

The changing populations, and climate and socio-economic conditions lead to changes in land allocation across Europe (Fig. 7). Under baseline socio-economic conditions, the selected climate scenario leads to little overall change in the area of intensive agriculture in Europe, although changing climate suitability for crops leads to changes in their spatial distribution. The increasing population in 'Should I Stay or Should I Go' combined with decreasing food imports, mechanisation and crop yields (associated with decreased GDP and a failure of innovation) and a reduction in demand for meat leads to a large increase in the area of land devoted to arable agriculture at the expense of extensive agricultural areas which are predominantly used for ruminants. However, a little changed population in 'We Are the World' combined with successful innovation for crop yields and agricultural mechanisation has led to a reduction in the agricultural area required to satisfy food demand.

The innovation in 'We Are the World' also extends to successfully reducing water demand, with significant increases in both irrigation efficiency and domestic and industrial water savings due to both technological improvements and behavioural change, which leads to a reduction in the number of river basins classed as having

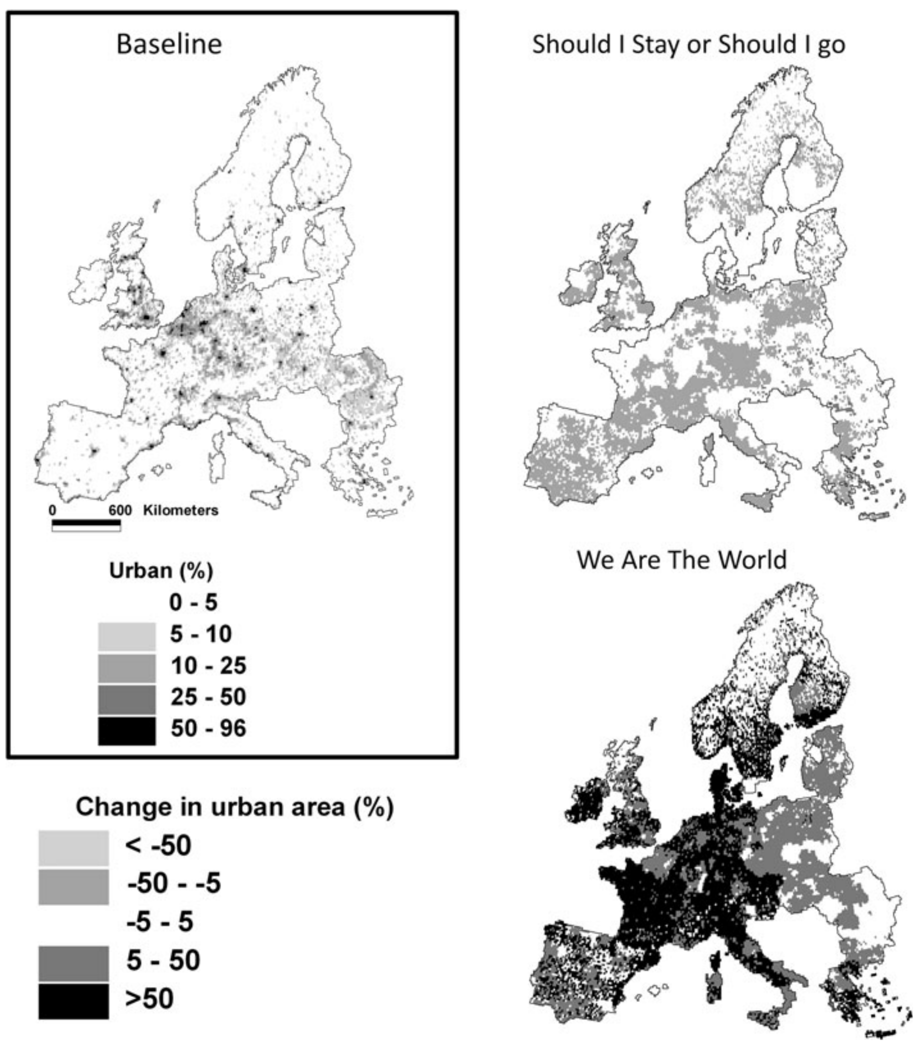

Fig. 6 The baseline areas of urban development and the changes under two of the CLIMSAVE socio-economic scenarios

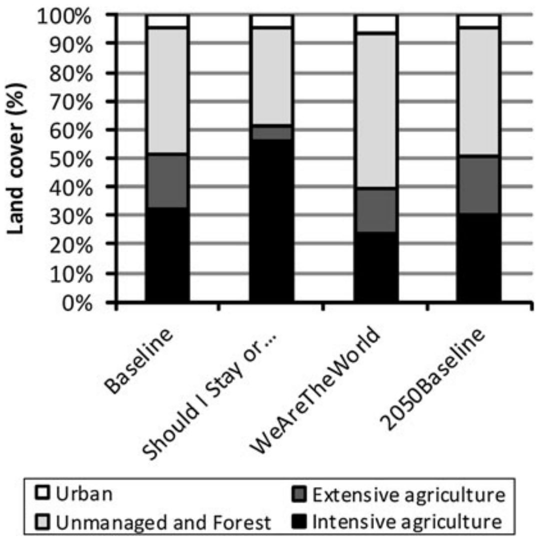

Fig. 7 Simulated land cover allocation under the baseline and a 2050s climate change scenario (with and without future socio-economic change; the latter labelled as '2050Baseline')

medium water stress (withdrawals-to-availability ratio of between 0.2 and 0.4; Flörke et al. 2011; Alcamo et al. 2007; Vörösmarty et al. 2000) and no river basins being severely water stressed (withdrawals-to-availability ratio of greater than 0.4). However, the failure of innovation solutions in 'Should I Stay or Should I Go', characterised by little change in irrigation efficiency and water savings due to behavioural change, and a reduction in domestic and industrial water savings due to technological deterioration lead to a fourfold increase in river basins with severe water stress under the selected climate scenario.

Discussion and conclusions

Participatory integrated assessment is a young field, which is contributing significantly to the understanding of complex human–environment systems. Kloprogge and van der Sluijs (2006) developed criteria for analysing PIA processes based on active or passive stakeholder involvement, bottom–up or top–down perspectives, and whether particular stages of the process were open or closed to participation. The active involvement of stakeholders through the stages of scenario development (Workshop 1), scenario quantification and exploration (Workshop 2 and web-based access to the IA Platform) and exploration of adaptation responses (Workshop 3 and web-based access to the IA Platform) within CLIMSAVE enables an integration of bottom–up or top–down perspectives and consistent socio-economic scenarios and model assumptions.

Overall, past experiences with operationalising the story-and-simulation approach to integrate qualitative and quantitative information have been positive. An important critical note, however, has been related to the manner in which quantitative model results are produced and communicated (see Kok et al. 2011b). The models that have been used are typically very complex with very long run-times. Models thus needed to be applied offline and were necessarily treated as a black box when communicated to stakeholders. This lowered the credibility of the results for stakeholders, particularly those that have no experience with mathematical models.

The fundamental concept underpinning the specification of the IA Platform is therefore to deliver rapid interactivity for the user to support PIA, for which the CLIMSAVE Platform utilises the World Wide Web. This technology provides a flexible and familiar interface to stakeholders, which should broaden accessibility and participation and increase impact in research communities. However, the CLIMSAVE IA Platform operates in an application area where trust and credibility are relevant issues, in that the modelling results produced by the Platform should be credible, whilst the modellers and users running and evaluating the model results should be trustworthy (Aumann 2011). A fundamental challenge for establishing credibility of models for the investigation of policy or adaptation responses to climate change is that the future impacts of the response have not yet occurred and thus the ability of the model to reproduce such future behaviour is uncertain (Aumann 2011).

The design of the CLIMSAVE IA Platform is based on addressing both of these issues. Firstly, trust is developed through (1) the iterative stakeholder engagement processes to ensure that there is stakeholder confirmation of the scenario-dependent model inputs; (2) clarity in the user's selection of the model inputs and responses, whether they be through scenario selection and/or slider positions that have produced the model output results; and (3) the CLIMSAVE IA Platform is freely accessible through the web ensuring that other users can reproduce and confirm prior simulation results and model settings. Credibility aims to be engendered through the scientific credibility of the meta-models (as demonstrated by the validation of the meta-models; Holman and Harrison 2011) and by allowing the users to rapidly interact with the IA Platform to establish whether the model behaviour reproduces their mental model (Kolkman et al. 2005) for their intended use of the model. The very short run-time allows for model execution during a stakeholder workshop, enabling direct stakeholder–model interaction which is rarely achieved within PIA activities. By experimenting with the online version and using immediate results, it is hypothesised that whilst the meta-models will not be totally transparent to lay persons, they will be regarded as a 'grey box' such that the stakeholders will gain confidence in model assumptions and model behaviour.

To further support the scientific credibility of the meta-models and integrated assessment approach, uncertainties related to the development of the meta-models, error propagation in integrated systems, the climate and socio-economic scenarios, and the cost estimates are being investigated. A version of the IA Platform is being created that can be run in batch mode allowing the research team to undertake large multiple runs on a dedicated server. The resulting database containing thousands of simulations will enable comprehensive analyses of these different sources of uncertainty and can be used to identify whether different representations of the future lead to divergence or convergence of vulnerability outcomes.

The final version of the CLIMSAVE IA Platform will be available from the end of 2012 from CLIMATE-ADAPT and the CLIMSAVE website (www.climsave.eu). It is anticipated that project partners will continue to maintain the tool after the project lifetime, but long-term maintenance will depend on the availability of further resources or agreements with CLIMATE-ADAPT. The meta-models within the Platform can be updated fairly easily with improved versions as long as the current input/output exchange data format is preserved. It is also possible to replace current data with new data but this is not currently an automatic process because the databases within the Platform are in unique formats associated with the specific meta-modelling approaches (e.g. clusters, trained neural network data and look-up tables). Future work could focus on developing OpenMI compliant meta-models (a standard for interconnecting data and models) which could allow automatic interconnection with external models and data complying with the same standard.

In their review of participatory IA, Salter et al. (2010) identify the relationship between 'choice, uncertainty and constraints' as a key cross-cutting theme in the conduct of past PIA. The scenario development process used in CLIMSAVE has allowed the exploration of future uncertainty that can expand and change the mental models of users (Salter et al. 2010) and more strongly represent the importance of qualitative information. As a consequence of this recognition that uncertainty is a structural feature of such complex problems (Wack 1985), adaptation decisions cannot be made based on the 'right' answers, but rather become a question of which choices might work best in the face of very different possible futures. Participatory IA platforms such as CLIMSAVE should seek to explore choices which inform the integration of adaptation actions and policies across sectors, such that unintentional adaptation resulting from actions in one sector does not reduce the effectiveness of purposeful adaptation in another sector, and to identify robust adaptation strategies which are scenario-independent or no-regret strategies (i.e. adaptation responses which will be beneficial for all future scenarios) (Holman and Harman 2008). However, it is recognised that complex human–environmental problems such as climate change are not solely defined by uncertainty and choice but bounded by real-world constraints (Salter et al. 2010). Future scenarios, and associated adaptation choices, are inevitably limited by future resource availability and environmental and institutional capacities. Such constraints are recognised within the CLIMSAVE IA Platform, through the key scenario uncertainties and qualitative assessment of resource availability identified by the stakeholders (based on the five capitals) which are used to constrain adaptation choices.

Given the vision for the CLIMSAVE IA Platform described in 'The IA Platform' section to assist stakeholders in developing their capacity to address regional/national/EU scale issues surrounding climate change, pragmatic decisions have inevitably had to be made to achieve an appropriate balance between spatial and temporal scale and system run-time. Greater complexity inevitably leads to increased model run-times and increased risk of users' disengaging with the Platform, thereby failing its vision. One of the key necessary limitations is the assumptions of independency of the three time slices (baseline, 2020s and 2050s), rather than time dependence, such that the implementation of the desired adaptation responses within a time slice is treated as the end-point within the modelling of that time slice, rather than treating adaptation as a feedback process with many different timescales of response, extending into the next time slice. However, this is partly addressed through allowing the user to vary the implementation time for each measure within the cost-effectiveness analysis. Nevertheless, despite such simplifications, the embedding of a thorough stakeholder engagement process; consideration of credibility and trust; and the realistic representation of choice, uncertainty and constraints within the CLIMSAVE IA Platform is intended to engender sufficient validity to ensure that it becomes a widely used tool within the European Climate Adaptation Platform (CLIMATE–ADAPT). As such, it will allow stakeholders to assess climate change impacts and adaptation strategies which are of interest to themselves, as well as exploring and understanding the interactions between different sectors, rather than viewing their own area in isolation. This will contribute to the development of a well-adapted Europe by building the capacity of decision-makers to understand cross-sectoral vulnerability to climate change and how it might be reduced by various cost-effective adaptation options.

Acknowledgments This work was supported by the CLIMSAVE Project (Climate change integrated assessment methodology for cross-sectoral adaptation and vulnerability in Europe; www.climsave.eu) funded under the Seventh Framework Programme of the European Commission (Contract No. 244031). CLIMSAVE is an endorsed project of the Global Land Project of the IGBP. The authors would like to thank all CLIMSAVE partners for their contributions to many productive discussions related to the content of this paper. Specific thanks to Jill Jäger for comments on the manuscript. The authors are also grateful to all stakeholders who participated in the project workshops and kindly offered their valuable input and to the facilitation team of Prospex.

References

Alcamo J (ed) (1994) Image 2.0: integrated modeling of global climate change. Kluwer, Dordrecht

Alcamo J, Döll P, Henrichs T, Kaspar F, Lehner B, Rösch T, Siebert S (2003) Development and testing of the WaterGAP 2 global model of water use and availability. J Hydrol Sci 48:317–337

Alcamo J, Flörke M, Märker M (2007) Future long-term changes in global water resources driven by socio-economic and climate changes. Hydrol Sci J 52(2):247–275

Annetts JE, Audsley E (2002) Multiple objective linear programming for environmental farm planning. J Oper Res Soc 53(9):933–943

Audsley E (1981) An arable farm model to evaluate the commercial viability of new machines or techniques. J Agric Eng Res 26(2):135–149

Audsley E, Pearn KR, Harrison PA, Berry PM (2008) The impact of future socio-economic and climate changes on agricultural land use and the wider environment in East Anglia and NorthWest England using a meta-model system. Clim Chang 90:57–88

Aumann CA (2011) Constructing model credibility in the context of policy appraisal. Environ Model Softw 26:258–265

Carmichael J, Tansey J, Robinson J (2004) An integrated assessment modelling tool. Glob Environ Chang 14:171–183

CCSP (2009) Best practice approaches for characterizing, communicating and incorporating scientific uncertainty in decision-making [Morgan GM, Dowlatabadi H, Henrion M, Keith D, Lempert R, McBride S, Small M, Wilbanks T (eds)]. A report by the Climate Change Science Program and the Subcommittee on Global Change Research. National Oceanic and Atmospheric Administration, Washington, DC. http://www.climatescience.gov/Library/sap/sap5-2/final-report/sap5-2-final-report-all.pdf. Accessed 11 Jan 2012

DEFRA (2008) Climate change policy cost-effectiveness indicator, PSA delivery agreement 27—Indicator 6, Department for Environment, Food and Rural Affairs, London. http://www.decc.gov.uk/assets/decc/statistics/analysis_group/cc_indicator/costeffect-psa-indicator6.pdf. Accessed 11 Jan 2012

Döll P, Kaspar F, Lehner B (2003) A global hydrological model for deriving water availability indicators: model tuning and validation. J Hydrol 270:105–134

Dubrovsky M, Simon K-H, Stuch B, Kok K, Harrison PA (2011) Report on the European driving force database for use in the integrated assessment platform. CLIMSAVE Deliverable 3.2. http://www.climsave.eu/climsave/doc/Report_on_the_database_of_European_drivers.pdf. Accessed 5 Dec 2011

European Commission (2009) White Paper on "Adapting to climate change: towards a European framework for action". European Commission COM 147, Brussels

Flörke M, Wimmer F, Laaser C, Viduarre R, Tröltzsch J, Dworak T, Stein U, Marinova N, Jaspers F, Ludwig F, Giupponi C, Bosello F, Mysiak J (2011) Climate adaptation—modelling water scenarios and sectoral impacts, no. DG ENV.D.2/SER/2009/0034

Giupponi C (2007) Decision support systems for implementing the European water framework directive: the MULINO approach. Environ Model Softw 22(2):248–258

Giupponi C, Mysiak J, Fassio A, Cogan V (2004) MULINO-DSS: a computer tool for sustainable use of water resources at the catchment scale. Math Comput Simul 64(1):13–24

Government Scottish (2009) Scotland's climate change adaptation framework. The Scottish Government, Edinburgh

Gramberger M, Kok K, Eraly E, Stuch B (2011a) Report on the first CLIMSAVE European stakeholder workshop. CLIMSAVE Deliverable 1.2a. http://www.climsave.eu/climsave/doc/Report_on_the_first_European_workshop.pdf. Accessed 5 Dec 2011

Gramberger M, Kok K, Eraly E, Stuch B (2011b) Report on the first CLIMSAVE regional stakeholder workshop. CLIMSAVE Deliverable 1.2b. http://www.climsave.eu/climsave/doc/Report_on_the_first_regional_workshop.pdf. Accessed 5 Dec 2011

Harrison PA, Berry PM, Butt N, New M (2006) Modelling climate change impacts on species' distributions at the European scale: implications for conservation policy. Environ Sci Policy 9(2):116–128

Holman IP, Cojocaru G (eds) (2010) Report describing the integrated assessment platform (IAP) specification, meta-model specifications and the multi-scale approach. CLIMSAVE Deliverable 2.1. http://www.climsave.eu/climsave/doc/Report_on_the_specification_of_the_IAP.pdf. Accessed 5 Dec 2011

Holman IP, Harman J (2008) Preliminary evaluation of the benefits of a participatory regional integrated assessment software. Clim Chang 90(1–2):169–187

Holman IP, Harrison PA (eds) (2011) Report describing the development and validation of the sectoral meta-models for integration into the IA platform. CLIMSAVE Deliverable 2.2. http://www.climsave.eu/climsave/doc/Report_on_the_Meta-models.pdf. Accessed 5 Dec 2011

Holman IP, Rounsevell MDA, Shackley S, Harrison PA, Nicholls RJ, Berry PM, Audsley E (2005) A regional, multi-sectoral and integrated assessment of the impacts of climate and socio-economic change in the UK. Clim Chang 71(1):9–41

Holman IP, Rounsevell MDA, Berry PM, Nicholls RJ (2008) Development and application of participatory integrated assessment software to support local/regional impact and adaptation assessment. Clim Chang 90:1–5

Hordijk L, Kroeze C (1997) Integrated assessment models for acid rain. Eur J Oper Res 102(3):405–417

Kenny GJ, Warrick RA, Campbell BD, Sims GC, Camilleri M, Jamieson PD, Mitchell ND, McPherson HG, Salinger MJ (2000) Investigating climate change impacts and thresholds: an application of the CLIMPACTS integrated assessment model for New Zealand agriculture. Clim Chang 46(1–2):91–113

Klein RJT, Schipper ELF, Dessai S (2005) Integrating mitigation and adaptation into climate and development policy: three research questions. Environ Sci Policy 8:579–588

Kloprogge P, van der Sluijs JP (2006) The inclusion of stakeholder knowledge and perspectives in integrated assessment of climate change. Clim Chang 75:359–389

Kok K, van Vliet M (2011) Using a participatory scenario development toolbox: added values and impact on quality of scenarios. J Water Clim Chang 2:87–105

Kok K, van Vliet M, Bärlund I, Dubel A, Sendzimir J (2011a) Combining participative backcasting and explorative scenario development: experiences from the SCENES project. Technol Forecast Soc Chang 78:835–851

Kok K, Bärlund I, Dubel A, Flörke M, Magnuszewski P, Sendzimir J, Van Vliet M (2011b) Lessons learnt: summary of scenarios:

multi-scale stories, conceptual models and policy actions. SCENES Deliverable 2.12, Wageningen University, Wageningen. www.environment.fi/syke/scenes. Accessed 3 Jan 2012
Kok K, Gramberger M, Simon K-H, Jäger J, Omann I (2011c) Report on the new methodology for scenario analysis, including guidelines for its implementation, and based on an analysis of past scenario exercises. CLIMSAVE Deliverable 3.1. http://www.climsave.eu/climsave/doc/Report_on_the_Scenario_Methodology.pdf. Accessed 1 Dec 2011
Kolkman MJ, Kok M, van der Veen A (2005) Mental model mapping as a new tool to analyse the use of information in decision-making in integrated water management. Phys Chem Earth 30:317–332
McFadden L, Spencer T, Nicholls RJ (2007) Broad-scale modelling of coastal wetlands: what is required? Hydrobiologia 577:5–15
Mokrech M, Nicholls RJ, Richards JA, Henriques C, Holman IP, Shackley S (2008) Regional impact assessment of flooding under future climate and socio-economic scenarios for East Anglia and North West England. Clim Chang 90:31–55
Morales P, Sykes MT, Prentice IC, Smith P, Smith B, Bugmann H, Zierl B, Friedlingstein P, Viovy N, Sabaté S, Sánchez A, Pla E, Gracia CA, Sitch S, Arneth A, Ogee J (2005) Comparing and evaluating process-based ecosystem model predictions of carbon and water fluxes in major European forest biomes. Glob Chang Biol 11–12:2211–2233
Murphy JM, Sexton DMH, Jenkins GJ, Boorman PM, Booth BBB, Brown CC, Clark RT, Collins M, Harris GR, Kendon EJ, Betts RA, Brown SJ, Howard TP, Humphrey KA, McCarthy MP, McDonald RE, Stephens A, Wallace C, Warren R, Wilby R, Wood RA (2009) UK climate projections science report: climate change projections. Met Office Hadley Centre, Exeter
Nordhaus WD (1994) Managing the global commons: the economics of climate change. MIT Press, Cambridge
Omann I, Jäger J, Grünberger S, Wesely J (2010) Report on the development of the conceptual framework for the vulnerability assessment. CLIMSAVE Deliverable 5.1. http://www.climsave.eu/climsave/doc/Report_on_Vulnerability_Framework.pdf. Accessed 15 Dec 2011
Owens S (2005) Making a difference? Some perspectives on environmental research and policy. Trans Inst Br Geogr 30:287–292
Pataki G, High C, Nemes G (2011) Report on the policy and governance context for adaptation. CLIMSAVE Deliverable 1.1. http://www.climsave.eu/climsave/doc/Report_on_the_adaptation_policy_analysis.pdf. Accessed on 1 Dec 2011
Pearson RG, Dawson TP, Berry PM, Harrison PA (2002) SPECIES: a spatial evaluation of climate impact on the envelope of species. Ecol Model 154:289–300
Reginster I, Rounsevell M (2006) Scenarios of future urban land use in Europe. Environ Plan B Plan Des 33:619–636
Richards J, Mokrech M, Berry PM, Nicholls RJ (2008) Regional assessment of climate change impacts on coastal and fluvial ecosystems and the scope for adaptation. Clim Chang 90:141–167
Rotmans J (1998) Methods for IA: the challenges and opportunities ahead. Environ Model Assess 3:155–179
Rotmans J (2006) Tools for integrated sustainability: a two-track approach. Integr Assess J 6(4):35–57
Rounsevell MDA, Metzger MJ (2010) Developing qualitative scenario storylines for environmental change assessment. Wiley Interdiscip Rev Clim Chang 1:606–619
Rounsevell MDA, Annetts JE, Audsley E, Mayr T, Reginster I (2003) Modelling the spatial distribution of agricultural land use at the regional scale. Agric Ecosyst Environ 95(2–3):465–479
Salter J, Robinson J, Wiek A (2010) Participatry methods of integrated assessment: a review. WIREs Clim Chang 1:697–717
Schneider SH (1997) Integrated assessment modelling of global climate change: transparent rationale tool for policy making or opaque screen hiding value-laden assumptions? Environ Model Assess 2:229–248
Schröter D, Cramer W, Leemans R, Prentice IC, Araújo MB, Arnell NG, Bondeau A, Bugmann H, Carter T, de la Vega-Leinert AC, Erhard M, Ewert F, Glendining M, House J, Kankaapää S, Klein RJT, Metzger M, Meyer J, Mitchell T, Lavorel S, Linder M, Reginster I, Rounsevell M, Sabaté S, Sánchez A, Sitch S, Smith B, Smith J, Smith P, Sykes MT, Thonicke K, Thuiller W, Tuck G, Zaehle S, Zierl B (2005) Ecosystem service supply and human vulnerability to global change in Europe. Science 310:1333–1337
Scottish Government (2011) Public bodies climate change duties: putting them into practice. The Scottish Government, Edinburgh
Shackley S, Deanwood R (2002) Stakeholder perceptions of climate change impacts at the regional scale: implications for the effectiveness of regional and local responses. J Environ Plan Manag 45:381–402
Sheppard S, Shaw A, Flanders D, Burch S, Wiek A, Carmichael J, Robinson J, Cohen S (2011) Future visioning of local climate change: a framework for community engagement and planning with scenarios and visualization. Futures 43:400–412
Sitch S, Smith B, Prentice IC, Arneth A, Bondeau A, Cramer W, Kaplan JO, Levis S, Lucht W, Sykes MT, Thonicke K, Venevsky S (2003) Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. Glob Chang Biol 9:161–185
Skourtos M, Kontogianni A, Tourkolias Ch (2011) Methodology for estimating the cost-effectiveness of adaptation options under uncertainty. CLIMSAVE Milestone 4.1, University of the Aegean, Mytilini
Sutherst RW, Maywald GF, Bottomley W, Bourne A (2001) CLIMEX v2 user's guide. CSIRO Entomol 12–13:281–299
Tinch R., Omann I, Jäger J, Harrison PA, Wesely J (2011) Report describing the adaptive capacity methodology. CLIMSAVE Deliverable 4.1. http://www.climsave.eu/climsave/doc/D4.1_Adaptive_capacity_method.pdf. Accessed on 15 Dec 2011
Trnka M, Kocmánková E, Balek J, Eitzinger J, Ruget F, Formayer H, Hlavinka P, Schaumberger A, Horáková V, Možný M, Žaluda Z (2010) Simple snow cover model for agrometeorological applications. Agric For Meteorol 150:1115–1127
Turnpenny J, Haxeltine A, O'Riordan T (2004) A scoping study of user needs for integrated assessment of climate change in the UK context: part 1 of the development of an Interactive Integrated Assessment Process. Integr Assess 4:283–300
Vafeidis AT, Nicholls RJ, McFadden L, Tol RSJ, Spencer T, Grashoff PS, Boot G, Klein RJT (2008) A new global coastal database for impact and vulnerability analysis to sea-level rise. J Coast Res 24(4):917–924
Van Asselt MBA, Rijkens-Klomp N (2002) A look in the mirror: reflection on participation in integrated assessment from a methodological perspective. Glob Environ Chang 12:167–184
Van der Sluijs JP (2002) Integrated assessment. In: Tolba MK (ed) Encyclopedia of global environmental change, vol 4., Responding to global environmental changeWiley, Chichester, pp 250–253
Van Notten PWF, Rotmans J, Van Asselt MBA, Rothman DS (2001) An updated scenario typology. Futures 35(5):423–443
Verzano K (2009) Climate change impacts on flood related hydrological processes: further development and application of a global scale hydrological model. PhD thesis, International Max Planck Research School on Earth System Modelling, University of Kassel
Vörösmarty CJ, Green P, Salisbury J, Lammers RB (2000) Global water resources: vulnerability from climate change and population growth. Science 289:284–288

Wack P (1985) Scenarios: uncharted waters ahead. Harv Bus Rev 5:72–89

Warrick RA, Ye W, Kouwenhoven P, Hay JE, Cheatham C (2005) New developments of the SimCLIM model for simulating adaptation to risks arising from climate variability and change. In: Zerger A, Argent RM (eds) MODSIM 2005. International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, Canberra, pp 170–176