



Differences between low-end and high-end climate change impacts in Europe across multiple sectors

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Abstract

The Paris Agreement established the 1.5 and 2 °C targets based on the recognition “that this would significantly reduce the risks and impacts of climate change”. We tested this assertion by comparing impacts at the regional scale between low-end (< 2 °C; RCP2.6) and high-end (> 4 °C; RCP8.5) climate change scenarios accounting for interactions across six sectors (agriculture, forestry, biodiversity, water, coasts and urban) using an integrated assessment model. Results show that there are only minor differences in most impact indicators for the 2020s time slice, but impacts are considerably greater under high-end than low-end climate change in the 2050s and 2080s. For example, for the 2080s, mitigation consistent with the Paris Agreement would reduce aggregate Europe-wide impacts on the area of intensive agriculture by 21% (on average across climate models), on the area of managed forests by 34%, on water stress by 14%, on people flooded by 10% and on biodiversity vulnerability by 16%. Including socio-economic scenarios (SSPs 1, 3, 4, 5) results in considerably greater variation in the magnitude, range and direction of change of the majority of impact indicators than climate change alone. In particular, socio-economic factors much more strongly drive changes in land use and food production than changes in climate, sometimes overriding the differences due to low-end and high-end climate change. Such impacts pose significant challenges for adaptation and highlight the importance of searching for synergies between adaptation and mitigation and linking them to sustainable development goals.

Keywords Paris agreement · High-end scenarios · Impacts · Cross-sectoral · Modelling

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Introduction

There is widespread acceptance that the climate is changing (IPCC 2014). The Paris Climate Agreement has set an international policy agenda towards achieving low-end climate change, where “low-end” refers to limiting global temperature increases to “well below 2 °C above pre-industrial levels” and “to pursue efforts to limit the temperature increase to 1.5 °C”. However, achieving such policy targets is challenging, particularly given that global mean surface temperatures are already reaching 1 °C above pre-industrial levels (Hansen et al. 2016; Hawkins et al. 2017; Kosaka and Xie 2016; Met Office 2015). Historic global emissions of greenhouse gases have been tracking the “high-end” of the latest generation of emission scenarios from the Intergovernmental Panel on Climate Change (IPCC) (Friedlingstein et al. 2014). If emissions continue to rise at historic rates, this has been estimated to lead to increases in global mean temperatures of 3.2–5.4 °C by 2100 (Fuss et al. 2014). Furthermore, national pledges of aggregate greenhouse gas emissions reductions under the Paris Agreement fall well short of those required to meet the agreed targets, with modelling studies estimating a median warming of 2.6–3.1 °C by 2100 for current Intended Nationally Determined Contributions (INDCs) (Rogelj et al. 2016). Hence, without more drastic emissions reductions, it seems likely that global average temperatures will rise above the Paris Agreement targets.

Whether climate change follows a low-end or high-end trajectory of warming will have significant implications for the impacts, risks and vulnerabilities experienced by environmental systems and socio-economic sectors. The 1.5 and 2 °C targets under the Paris Agreement were established based on the recognition “that this would significantly reduce the risks and impacts of climate change”. Climate change impacts have been extensively studied for specific sectors at a range of scales, for example agriculture (Moore and Lobell 2014; Trnka et al. 2014), forestry (Bugmann et al. 2017; Mina et al. 2017), biodiversity (Markovic et al. 2014; Thom et al. 2017), water (Feyen et al. 2012; Molina-Navarro et al. 2014) and coasts (Neumann et al. 2015; Ramsbottom et al. 2012). However, most of these studies cover intermediate to higher-end climate change scenarios (with mean temperatures ranging from ~2 to 4 °C), although a few recent studies have focused on impacts under low-end climate change that is consistent with the Paris Agreement targets (Sanderson et al. 2017). Furthermore, even fewer studies have compared impacts of low-end (<2 °C) and high-end (>4 °C) climate change, and those which have tend to focus on single sectors or a limited range of indicators, and the global scale (e.g. Arnell and Lloyd-Hughes 2014; Hirabayashi et al. 2013; Prudhomme et al. 2014).

Differences between low-end and high-end climate change may lead to altered interactions between different sectors and

scales highlighting the importance of employing a systematic approach for modelling impacts and vulnerabilities that takes account of cross-sectoral interactions. Yet, many climate change impact assessments apply models of individual sectors such as agriculture, forestry and water without considering the complex interdependencies within human and environmental systems (Harrison et al. 2015a), thereby misrepresenting the spatial pattern, direction and magnitude of impacts (Harrison et al. 2016). Furthermore, impacts under low-end or high-end climate change scenarios are likely to interact with changes in future socio-economic conditions, as represented by socio-economic scenarios. Impacts resulting from socio-economic scenarios can be greater than impacts based on climate change scenarios alone (Audsley et al. 2015; Holman et al. 2016; Wimmer et al. 2015). Moreover, it is often through the socio-economic drivers that cross-sectoral impacts become evident, as policy effects in one sector can have indirect effects in others (Harrison et al. 2016).

This paper advances existing climate change impact assessment studies by investigating the differences in impacts between low-end and high-end climate change scenarios on Europe and its regions using a regional integrated assessment model, which simulates impacts of multiple drivers on six sectors (agriculture, forestry, biodiversity, water, coastal and urban) and their cross-sectoral interactions. The model is utilised to analyse how the spatial patterns and magnitudes of impacts differ between low-end (as represented by Representative Concentration Pathway (RCP) 2.6; Van Vuuren et al. 2011) and high-end (as represented by RCP 8.5) climate change scenarios. Furthermore, it is applied to examine how the different climate futures (RCPs 2.6 and 8.5) interact with different socio-economic futures (as represented by the Shared Socioeconomic Pathways, SSPs) to produce different spatial patterns and magnitudes of impacts and vulnerability. Model results are interpreted to answer the following questions:

- (i) How much do impacts differ between low-end and high-end climate change?
- (ii) When do the benefits of emissions reductions in terms of significantly reducing impacts become apparent given scenario uncertainties?
- (iii) Who are the winners and losers under low-end and high-end climate change?
- (iv) How do the winners and losers change under different socio-economic scenarios?

Methods

The IMPRESSIONS Integrated Assessment Platform (IAP2) is used to simulate the impacts of low-end and high-end

climate and socio-economic changes on multiple sectors. The IAP2 is an extension of the CLIMSAVE Integrated Assessment Platform (IAP1; Harrison et al. 2015b, 2016). It integrates a suite of ten sectoral models representing agriculture, forestry, biodiversity, water resources, fluvial and coastal flooding and urban development within a web-based platform. To facilitate the cross-sectoral model linkages and to reduce model runtime, a meta-modelling approach was used whereby computationally efficient or reduced form models that emulate the performance of more complex models were developed (Harrison et al. 2013). The IAP2 operates at a spatial resolution of 10 arcmin \times 10 arcmin (approximately 16 km \times 16 km) across Europe (the EU28 plus Norway and Switzerland) and produces outputs of both sector-based impact and vulnerability indicators and ecosystem services in order to link climate change impacts directly to human well-being (Harrison et al. 2015a).

The IAP2 includes quantifications of three RCPs (2.6, 4.5 and 8.5) and four SSPs (1, 3, 4 and 5) out to 2100; only RCP2.6 and RCP8.5 are used in this paper to represent low-end and high-end climate change, respectively. For each RCP, three combinations of global climate model (GCM) and regional climate model (RCM) were selected from available climate models to represent uncertainty over future climate change in Europe, particularly spatial differences between climate scenarios (Madsen et al. 2016). However, climate models with a high climate sensitivity were selected for RCP8.5 and models with low/medium sensitivity for RCP2.6 to better distinguish low-end and high-end climate change. The three GCM/RCM combinations for RCP2.6 were (i) EC-EARTH/RCA4; (ii) MPI-ESM-LR/REMO; and (iii) NorESM1-M/RCA4. For RCP8.5, they were (i) HadGEM2-ES/RCA4; (ii) CanESM2/CanRCM4; and (iii) IPSL-CM5A-MR/WRF. Europe-wide changes in annual mean temperature range from 1.3 to 1.4 °C under the RCP2.6 climate scenarios and from 4.7 to 5.4 °C under the RCP8.5 scenarios for 2071–2100 compared to 1961–1990 (see Online Resource 1 for the spatial distributions of annual and seasonal temperature and precipitation change under each climate scenario).

European versions of four of the global SSPs (O'Neill et al. 2017) were created by mapping existing European stakeholder-developed socio-economic scenarios to the global SSPs using an expert workshop to further enrich their narratives and trends in key socio-economic variables (see Kok et al. 2018, this issue for further details). The scenarios were then quantified for use in the IAP2 using a combination of fuzzy sets and modeller expertise to structure and capture uncertainty for each variable (see Pedde et al. 2018, this issue for further details and Online Resource 2 for the quantification of the socio-economic scenario drivers). The four SSPs were (i) SSP1—We are the World, where there is a high commitment to achieve sustainable development goals through

effective governments and global cooperation, ultimately resulting in less inequality and less resource intensive lifestyles; (ii) SSP3—Icarus, where economic woes in major economies and regional conflict lead to increased antagonism between and within regional blocs resulting in the disintegration of social fabric and many countries struggling to maintain living standards; (iii) SSP4—Riders on the Storm, where power becomes concentrated in a relatively small political and business elite leading to large disparities in economic opportunity with substantial proportions of populations having a low level of development; and (iv) SSP5—Fossil-fuelled Development, where people place increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress, but a lack of environmental concern leads to the exploitation of abundant fossil fuel resources.

To explore the impacts under a range of combined climatic and socio-economic futures, the IAP2 was run for 91 different scenario combinations:

- Baseline (1 run): The baseline climate is represented by the CRU climatology for 1961–1990 (New et al. 2002); baseline socio-economic settings represent 2000–2010;
- Low-end climate change scenarios alone: RCP2.6 for three GCM/RCMs for the 2020s, 2050s and 2080s time slices (9 runs);
- High-end climate change scenarios alone: RCP8.5 for three GCM/RCMs for the 2020s, 2050s and 2080s time slices (9 runs); and
- Combined climate and socio-economic scenarios: all combinations of climate change scenarios and SSPs for the 2020s, 2050s and 2080s time slices (72 runs).

Indicators were selected to reflect impacts across sectors. These included *land use-related indicators* including the area of the following: arable land; intensive grassland (dairy); extensive grassland (sheep and rough grazing); very extensive grassland (extremely poor grazing, heath and moor); managed forest (for timber); unmanaged land (where land has no productive purpose) and unmanaged woodland (where unmanaged land occurs which is dominated by trees through ecological succession). They also included indicators related to food production (TJ of energy produced across all food sources); carbon sequestration (Mt of carbon stored in forests); irrigation usage (m³ year⁻¹); water exploitation index (ratio of total water used in industry, domestic, power and agricultural sectors to water availability); flooding (number of people flooded in a 1 in 100 year event) and biodiversity (change relative to baseline in the number of the 105 species modelled that have both climate and habitat space; the model assumes species are capable of dispersing to access any new space made available within the time slice, which underestimates the real vulnerability of some species).

Results

Impacts under the climate-only scenarios

Changes in the impact indicators under the low-end (RCP2.6) and high-end (RCP8.5) climate change scenarios (assuming baseline socio-economics) are shown in Fig. 1a (and Online Resource 3). Impacts are clearly greater under the high-end scenarios compared to the low-end scenarios. For example, only one indicator (unmanaged woodland) increases by more than 50% relative to baseline under the low-end climate scenarios, whilst eight indicators (extensive grassland, managed forest, very extensive grassland, unmanaged land, unmanaged woodland, carbon sequestration, water exploitation index and irrigation usage) either increase or decrease by more than 50% under the high-end scenarios. The different climate models lead to different spatial patterns in impacts which in turn lead to different Europe-wide aggregate changes in the impact indicators between scenarios (as shown in Fig. 1a). Overall, impacts vary to a greater extent between RCPs than between climate models for the same RCP, particularly after the 2020s, although this may be due to the selection of climate models. Differences between climate models are also greater for the high-end than for the low-end scenarios. For example, the greatest differences between climate models for the unmanaged land indicator are -3% , relative to baseline, for RCP2.6 and $+55\%$ for RCP8.5.

There are clear differences in the impacts of the low-end and high-end climate scenarios on the indicators related to the agricultural and forestry sectors. Under low-end scenarios, changes are within $\pm 20\%$ of baseline across most land use indicators. In general, under RCP2.6, arable land and managed forest are projected to decrease in the majority of time periods and scenarios, whilst intensive grasslands, very extensive grassland and unmanaged woodland increase. Unmanaged land shows little change whilst extensive grassland shows a mixed trend depending on the climate model used. Under high-end scenarios, changes in land use are considerable with large increases projected in marginal lands (unmanaged woodland (up to 490%), very extensive grasslands (277%) and unmanaged land (178%)) and substantial decreases in the areas of extensive grassland (up to -98%), managed forest (-55%) and intensive grassland (-32%). Irrigation usage increases under all scenarios, but increases to a much greater extent under high-end (by 230–260%) than low-end (120–130%) scenarios. Likewise, carbon sequestration changes little under the low-end scenarios, but under high-end climate change, the increase in total forest cover (with the increase in unmanaged woodland compensating for the decline in managed forest) leads to an increase of carbon storage by 30 to 80%. Arable land changes only a small amount under all the climate-only scenarios, due to the constant food demand, mainly decreasing by up to -6% under

low-end scenarios and decreasing by up to -19% under high-end scenarios.

Other indicators show similar patterns of change in the magnitude of impacts between low-end and high-end climate scenarios. The number of people flooded increases under both RCPs due to increased fluvial and coastal flooding, but to a greater extent under RCP8.5 particularly in the 2080s time slice (by up to $+33\%$) due to significantly higher projected sea level rise. Biodiversity vulnerability changes very little under the low-end scenarios ($<3\%$); however, under high-end scenarios where land use change is more dramatic and climate change more extreme, there is a decrease in the number of species with suitable climate and habitat space to between 78 and 95% of baseline depending on the climate model. Water stress (as indicated by the Water Exploitation Index) increases in all climate scenarios by up to 3 and 18%, relative to baseline, under low-end and high-end climate change, respectively.

There is a significant increase in the magnitude of impacts after the 2050s when differences between low-end and high-end climate change become apparent. However, trends over the three time slices (2020s, 2050s and 2080s) are often non-linear and some exhibit inflexions with an initial increase/decrease to the 2050s followed by a reverse of the trend to the 2080s. The choice of climate model (GCM/RCM) affects the temporal trend in impacts under both low-end and high-end climate scenarios, although the magnitudes of the inflexions are greater under the RCP8.5 scenarios. For example, a steady increase in unmanaged woodland area is projected for the EC-EARTH/RCA4 climate model for RCP2.6 up to c.225% of baseline levels in the 2080s. Alternatively, the other two climate models for RCP2.6 project an initial increase in unmanaged woodland area (to c.200% of baseline levels) followed by a steep decline in the 2080s, which for MPI-ESM-LR/REMO brings unmanaged woodland area close to baseline levels (125% of baseline). For RCP8.5, projections in unmanaged woodland area diverge across the climate models from a non-linear increase to 500% of baseline levels (under IPSL-CM5A-MR/WRF in the 2080s) to an increase to 416 and 365% in the 2050s followed by a decline to 335 and 344% in the 2080s (under CanESM2/CanRCM4 and HadGEM2-ES/RCA4, respectively). These different temporal trends are likely to reflect changes in growing conditions for different tree species with optimum thresholds being reached and/or exceeded at different times under the different climate models.

Impacts under the combined climate and socio-economic scenarios

Changes in the impact indicators under the combined climate (RCPs 2.6 and 8.5) and socio-economic (SSPs 1, 3, 4 and 5)

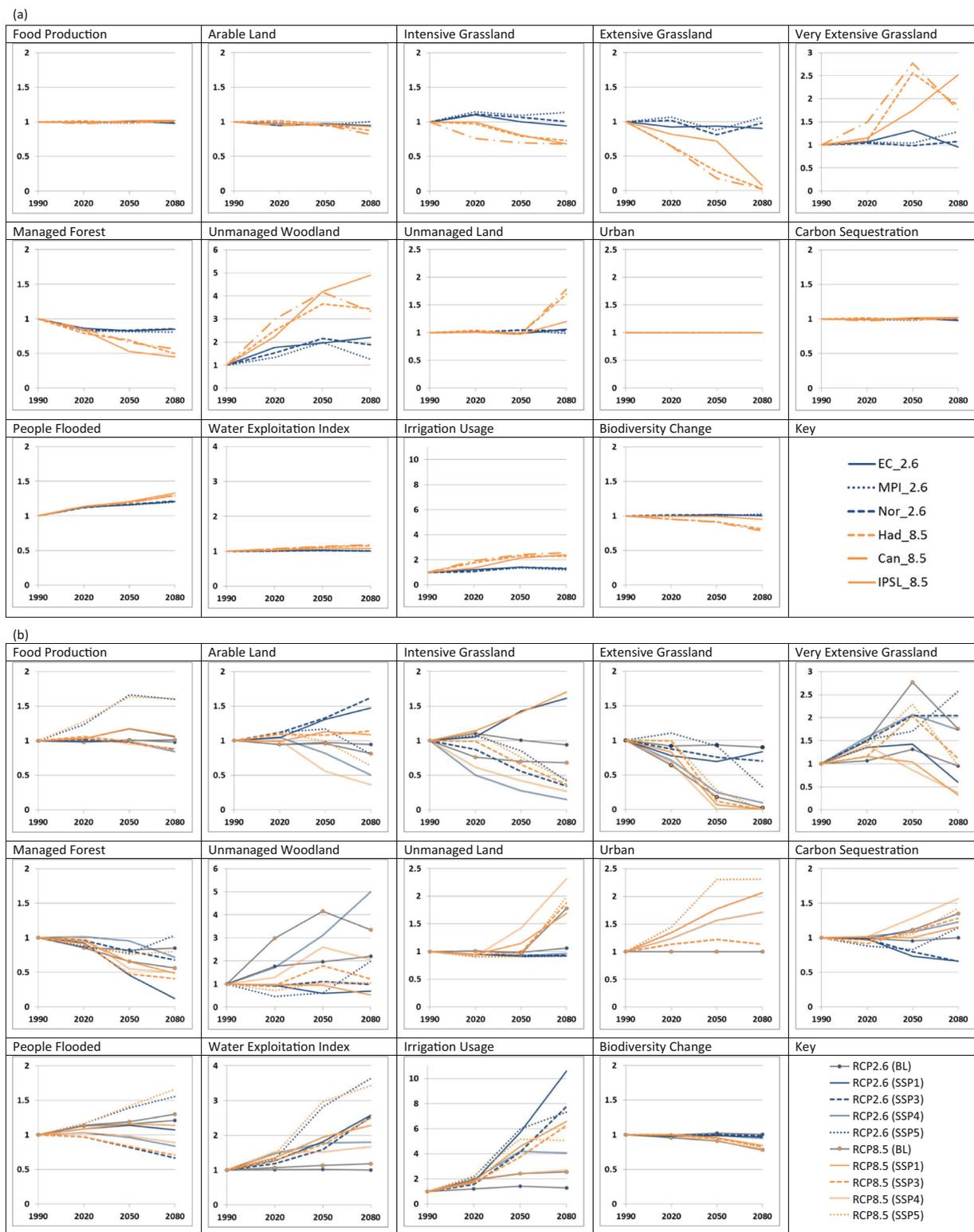


Fig. 1 Changes in impact indicators under **a** climate-only (RCP2.6 and RCP8.5) and **b** combined climate (RCP2.6 and RCP8.5) and socio-economic scenarios (SSPs 1, 3, 4 and 5). Values shown are Europe-wide averages as a proportion of baseline values (i.e. baseline = 1). For **a**, three climate models (GCM/RCM) are shown for each RCP as follows: EC_2.6 (EC-EARTH/RCA4), MPI_2.6 (MPI-ESM-LR/REMO), Nor_

2.6 (NorESM1-M/RCA4), Had_8.5 (HadGEM2-ES/RCA4), Can_8.5 (CanESM2/CanRCM4) and IPSL_8.5 (IPSL-CM5A-MR/WRF). For **b**, only one climate model (GCM/RCM) is shown for RCP2.6 (based on EC-EARTH/RC4A) and RCP8.5 (based on CanESM2/CanRCM4). BL baseline socio-economic inputs

scenarios are shown in Fig. 1b (and Online Resource 3). Including changes in socio-economic conditions, in addition to low-end or high-end climate change, results in substantially greater magnitudes of changes in the majority of impact indicators, with all (except biodiversity) showing changes in excess of $\pm 50\%$ of baseline values in at least one scenario. Furthermore, there is considerably greater variation in the range and direction of change between the SSPs compared to that seen between the climate models: intensive grassland, arable land, very extensive grassland, people flooded and carbon sequestration all show positive trends in some SSPs and negative trends in others.

Moreover, for some indicators, the socio-economic scenario is shown to be driving the trend rather than the climate scenario. For example, the urban land use indicator is solely driven by socio-economic factors, such as changes in GDP, population, land use planning regulations and societal preferences. However, changes in urban land use have knock-on effects for the land available for other land uses, which may be affected by changes in both climate and socio-economic factors. A more nuanced example is for the arable land use indicator which is projected to increase under SSPs 1 and 3 (where food imports decrease significantly), with a substantially greater increase under RCP2.6 compared to RCP8.5. This reflects increases in crop yields that are possible under the more extreme warming of RCP8.5 in northern regions of Europe enabling more food production in less land area. Under SSPs 4 and 5 (where food imports increase), arable land use decreases for both RCPs, with SSP4 requiring considerably less arable land area than SSP5 due to a notable decline in population with time, which has a greater influence on the land system than climate through changes in food demand. This is not to say that the changes in climate play no role, but that the significance of this role varies depending on the impact indicator and the socio-economic changes taking place simultaneously.

To further exemplify the relationships between the climate and socio-economic drivers and the trends in impact indicators, we describe in detail projections from the two SSPs that result in the greatest differences in impacts: SSP1 (We are the World) and SSP4 (Riders on the Storm). SSP1 is characterised by an increase in population, a decline in food imports, greater agricultural mechanisation, reduced dietary preferences for meat, increased water savings through technology and behavioural change, and a focus on environmental sustainability reflected by a more extensive approach to agriculture with lower crop yields and lower fertiliser use to reduce diffuse pollution (see Online Resource 2). Under the low-end climate scenarios associated with RCP2.6, this leads to a considerable increase in intensive agriculture: the sum of arable land plus intensive grassland increases from 36% of total land area at baseline to more than 50% in the 2050s and 2080s. This is driven by the need to meet increased food demand due to the

increasing population and reducing imports, existing agricultural land being more extensively managed than currently for environmental purposes and a shift from meat to dairy products. In addition, urban growth has a notable impact on land availability.

Agricultural expansion in SSP1 happens at the expense of forestry which increasingly declines, both in terms of managed forest and unmanaged woodland. In the 2080s, the IAP2 is unable to find an iteration that meets 100% of food and timber demand: food demand for cereals, oils, meat and protein are met, but only between 93 and 95% of the demand for roots, fibre and milk and only 8% of the demand for timber are met. Thus, the final balance of land use does not meet the requirements of society and further imports would be needed, or society would need to adapt to live with less. Under the high-end scenarios associated with RCP8.5, total intensive agriculture expands relative to baseline, but to a lesser extent than under the RCP2.6 scenarios—only expanding from 36 to 40% with grassland expansion considerably lower than in RCP2.6. As a result, forest retraction is less than is seen under RCP2.6. The substantial increases in intensive agriculture also lead to large increases in irrigation usage under both RCPs (> 650% in the 2080s; driven in RCP2.6 by the large-scale land use changes and in RCP8.5 by a combination of land use change and the extreme climate change). This in turn results in greater water stress (as indicated by the water exploitation index), which more than doubles in both RCPs.

SSP4 is characterised by a declining population, an increase in food imports, greater agricultural mechanisation, increased dietary preferences for consuming white meats (pork and chicken), no change in dietary preferences for consuming red meat (beef and lamb) and a low focus on environmental protection with fertilisers applied at optimum levels and yields increased through technological innovation and intensive land management (see Online Resource 2). Compared to SSP1 and baseline, the willingness of society to increase dependence on external food imports and the decreasing population removes considerable pressure on the food demand that needs to be met from Europe's own agricultural system. Furthermore, the high-tech and intensive land management means that greater yields are possible from the same unit of land. Under the low-end climate scenarios associated with RCP2.6, this results in European intensive agriculture declining significantly from 36% of the land surface at baseline to less than 25% in the 2050s and less than 15% in the 2080s. Consequently, total forest/woodland area expands considerably from baseline to 54% of land area, though managed forest declines slightly due to increased timber yields.

Under the high-end climate scenarios associated with RCP8.5, the overall trends in impacts are similar; however, the land area required to meet demand declines even further: from 36% at baseline to 17% in the 2050s and 11% in the 2080s. This suggests that the increased temperatures improve

yields in parts of Europe that are currently temperature-limited to a position that this is possible. However, the total forest area is not as great under RCP8.5 suggesting that current tree species in managed forests and unmanaged woodland have become climatically stressed. Despite the reduction in agricultural area, the highly intensive nature of agriculture in SSP4 results in an increase in irrigation usage of +170% (although this is significantly less than the increase under SSP1), which in turn contributes to greater water stress (but to a lesser degree than under SSP1).

Spatial variability in impacts

There is considerable spatial variability in impacts under the different scenarios that is not apparent in the Europe-wide aggregate changes shown in Fig. 1. Regional changes in impact indicators for the 2080s time slice are shown in Fig. 2, which summarises impacts for five sub-regions of Europe, and Fig. 3, which shows spatial patterns of impact indicators associated with the food-water nexus (see also Online Resource 4). Under the climate change-only scenarios, much greater impacts are projected for all regions under high-end than low-end climate change. More specifically, there are large shifts in the land use-related indicators under high-end climate change leading to new patterns of “winners and losers” with regard to agricultural and forest productivity, water stress, flooding and biodiversity vulnerability.

Arable land shifts northwards under RCP8.5 and, hence, the *Northern* and *Alpine* regions show increases in food production achieved through greater land area dedicated to arable land rather than grasslands, and in the *Alpine* region managed forest. However, carbon storage is projected to increase in both regions due to the expansion of unmanaged woodlands. *Northern* Europe is the only region where biodiversity vulnerability improves due to new climate and habitat space becoming available, although this assumes the species are able to disperse quickly enough to access these new opportunities.

In contrast, *Southern* and *Atlantic* regions show decreases in the areas of arable land, productive grasslands and managed forest (with large losses in arable land in England and much of southern Europe), but substantial increases in marginal or unmanaged land area. Some parts of southern Europe continue arable production under RCP8.5, but with considerable irrigation usage (see Online Resource 4, Fig OR4a). Irrigation also increases in northwest regions of Europe with knock-on consequences for water stress. Virtually all river basins in southern Europe and many in northwest Europe are classified as experiencing severe water stress ($WEI > 0.4$) under high-end climate change. Large decreases in biodiversity are also projected in both the *Southern* and *Atlantic* regions as well as large increases in the number of people flooded in the *Atlantic* region. The *Continental* region shows only small changes in arable land area, but a changing intensity of

grassland production to very extensive or unmanaged. Similarly managed forest is projected to decline, whilst unmanaged woodland expands resulting in increases in carbon sequestration. Biodiversity is also projected to decline in the *Continental* region.

Similar directions of change are shown for the low-end (RCP2.6) climate change scenarios, but the magnitude of change in each region is much less severe, with changes in water stress, biodiversity, carbon sequestration and unmanaged land area changing by less than 25% in all regions. In the *Southern* region, water stress (as indicated by changes in the water exploitation index) reduces from +100% relative to baseline under RCP8.5 to +9% under RCP2.6. Flood impacts in the *Atlantic* region are also lessened under the RCP2.6 scenario to a 48% increase relative to baseline compared to a 70% increase under RCP8.5. Land use changes still take place under low-end climate change and there are distinct regional patterns in them, but the levels of the changes are substantially lower than those driven by the high-end climate change scenarios (see Online Resource 4; Fig OR4c).

The combined climate and socio-economic scenarios result in different spatial patterns of impacts depending on the SSP and whether it is combined with low-end or high-end climate change. Urban area (which is not affected by climate) is projected to increase in all regions under all SSPs, except SSP3, which has fairly substantial reductions in population (−38% in the 2080s) and slow GDP growth. In *Northern* and to some extent *Alpine* regions, food production and arable land area increase under all SSPs, except SSP4, where additional arable land is not needed due to increased food imports, decreased population and improved high-tech agricultural productivity. Increases are greatest in SSP1 where arable land expands considerably northwards and eastwards under both RCPs due to reduced food imports, a greater population and more environmentally friendly agriculture resulting in a need for greater agricultural land area to meet food demand. There is some contraction in arable land in western and northwestern areas of Europe (UK, France, Portugal, the Netherlands, Denmark) for RCP8.5 compared to RCP2.6 and baseline due to higher yields in northern Europe under the more extreme increases in temperature. Grasslands also become more intensively managed in *Northern* and *Alpine* regions under SSP1, but substantially reduce in the other SSPs. As a result of these changes in agriculture, irrigation usage increases massively in these regions compared to the climate-only scenarios, particularly in SSP1 where it increases by more than 2000% under RCP8.5 relative to the low baseline level (see Fig OR4a).

In *Southern* Europe, food production increases under SSPs 4 and 5 even though the area of intensively farmed land decreases due to improvements in agricultural technology resulting in more food being produced per unit of land. Conversely, food production decreases under SSPs 1 and 3

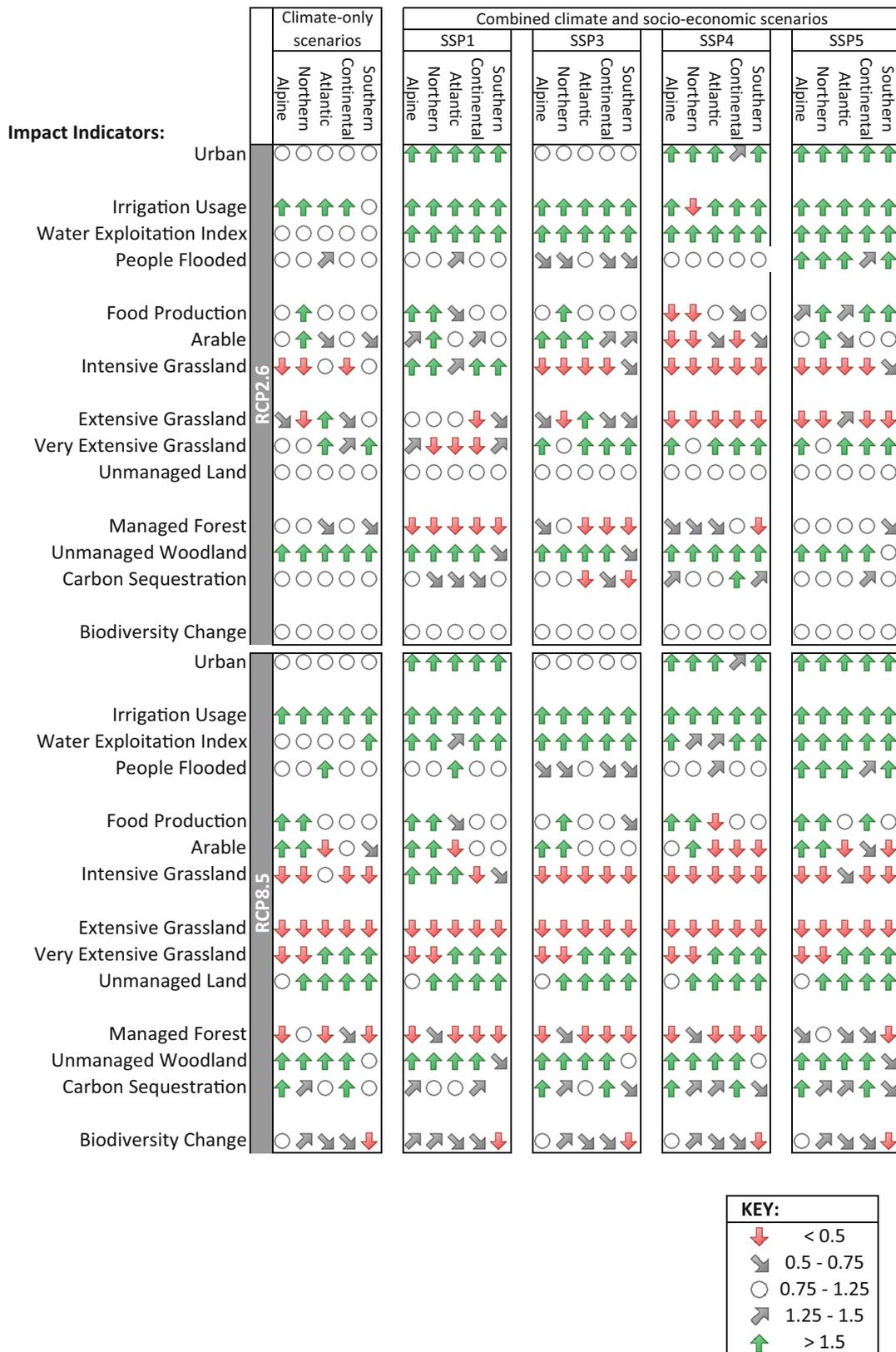


Fig. 2 Summary of changes in impact indicators for the 2080s resulting from climate-only and combined climate and socio-economic scenarios for five regions within Europe. Symbols represent the magnitude of

change in the impact indicator for each region relative to baseline calculated as “scenario value” divided by “baseline value” (see Online Resource 4 for values behind the symbols and definition of regions)

due to decreases in either arable or intensive grassland when the SSPs are combined with RCP2.6 or both with RCP8.5. Very extensively managed grassland increases in *Southern* Europe under all SSPs. Irrigation usage also increases relative to both baseline and the climate-only scenarios. The *Atlantic* region shows decreases in food production related to decreases in arable land and mixed impacts on grasslands depending on the scenario, except in the SSP5 × RCP2.6 scenario where food production is projected to slightly increase. The *Continental* region shows only small changes in food production, except in SSP5 where it increases even though the area of arable and intensive grassland declines due to increases in productivity driven by technology and climate.

Managed forest decreases in all regions, most severely in SSP1 combined with RCP2.6 due to the large-scale expansion of agriculture. Conversely, unmanaged woodland is projected to increase in all regions, except *Southern* Europe. Consequently, carbon sequestration increases in all regions, except *Southern* Europe. The direction of change in biodiversity also changes little between the SSPs, with improving biodiversity in *Northern* and *Alpine* regions, where new climate space becomes available (assuming species can disperse to access it), and reducing biodiversity in *Southern*, *Continental* and *Atlantic* regions. These trends are the same when the SSPs are combined with both RCPs, but the magnitude of change is greater for RCP8.5. By contrast, trends in the number of people flooded vary considerably between the SSPs, with decreases in SSPs 3 and 4, where population decreases, and increases in SSPs 1 and 5, where population increases. In general, the *Atlantic* region is the most sensitive to flooding out of the five European regions under all SSPs.

Discussion

Differences in impacts between low-end (c.1.5 °C) and high-end (c.4 °C) climate change have been analysed using a regional integrated assessment model covering multiple sectors and their cross-sectoral interactions for Europe. This has advanced assessment of climate change impacts by (i) quantifying and comparing very low and high levels of climate change; (ii) assessing how such impacts vary with and without socio-economic change; (iii) considering interactions between sectoral impacts under different levels of climate and socio-economic change for multiple indicators covering a range of land and water sectors; and (iv) investigating aggregated and spatially explicit implications of such scenarios at the regional scale for Europe.

It is important when reflecting on the changes presented to understand these in the context of the way that the modelling system makes its decisions on land use allocation. Within the IAP2, decisions are driven primarily by long-term land use profitability within the constraints of climatic conditions and soils, and taking into consideration the need to meet total

European food demand minus the net proportion of food demand imported from outside the EU (a scenario input parameter). Consequently, commodities are created in the areas where conditions are best suited to them and profitability and competitiveness are highest. Whilst this is a reasonable assumption in many ways, it does not take into consideration a number of other factors driving and limiting land use change, such as inertia, displacement of impacts to countries outside Europe, national political priorities and local societal preferences and awareness. Many of these aspects could be further enhanced through agent-based modelling (Brown et al. 2017; Holzhauser et al. 2018, this issue), which can represent more diverse decision-making processes (e.g. Acosta-Michlik et al. 2014; Blanco et al. 2017; Murray-Rust et al. 2013). However, whilst the spatial patterns of land use might change, the biophysical limits will not and as such the key messages resulting from the IAP2 simulations with respect to winners and losers, the most and least productive areas, and the cross-sectoral challenges of balancing demands across sectors remain of great significance. Here, we highlight these key messages in relation to the four questions posed in the “[Introduction](#)”.

How much do impacts differ between low-end and high-end climate change, and when do these differences become apparent?

Results for the climate-only scenarios show that impacts under high-end climate change scenarios are significantly greater than impacts under low-end scenarios in all socio-economic sectors and environmental systems. Under low-end climate change, Europe-wide aggregate impacts are between ± 5% of baseline values, on average across climate models, in the 2080s for most indicators (food production, arable land, intensive grassland, extensive grassland, carbon sequestration, water exploitation index, biodiversity vulnerability and unmanaged land). For the other indicators, impacts are still substantially lower under low-end compared to high-end climate change in the 2080s (managed forests: 34%, flooded people: 10%, irrigation usage: 113%, unmanaged woodland: 212%). Land use change is considerably greater under high-end compared to low-end scenarios, with large reductions in productive land and increases in unmanaged or abandoned land as currently suitable tree species and existing agricultural practices struggle to cope with the extreme climatic conditions.

This supports the statement in the Paris Agreement that the policy targets of 2 and 1.5 °C “would significantly reduce the risks and impacts of climate change” and is consistent with global findings. Arnell and Lloyd-Hughes (2014) concluded that exposure to increased water resource scarcity would be reduced globally in 2080 by 27–32% under RCP2.6 compared to RCP8.5, and exposure to increased flood frequency would be reduced by around 33%. Hirabayashi et al. (2013) also showed that the annual global flood exposure increases by about 4 times from current

under RCP2.6 compared to about 14 times under RCP8.5 by the end of the twenty-first century. In addition, Prudhomme et al. (2014) found that the global severity of hydrological drought at the end of the twenty-first century was systematically greater for RCPs describing stronger radiative forcings.

Differences between the low-end and high-end climate-only scenarios (and hence the benefits associated with emissions reductions in significantly reducing impacts) tend to only become apparent from the 2050s time slice onwards, with the exception of irrigation usage which already increases by 13% on average under RCP2.6 and 69% under RCP8.5 in the 2020s. In addition, some land use classes show fairly large differences between low-end and high-end scenarios in the first (2020s) time slice, particularly intensive and extensive grasslands which show different directions of change, increasing or changing little under RCP2.6 and decreasing by 9 and 30%, respectively, under RCP8.5. However, the range of uncertainty due to the three climate models is generally greater than the difference between low-end and high-end climate change for most indicators in the 2020s time slice. The only exceptions are for unmanaged woodland and extensive grassland. This is consistent with Hawkins and Sutton (2009) who showed that uncertainty in regional climate predictions is dominated by model uncertainty and internal variability for the next few decades.

In general, impacts become stronger over time when averaged across climate models, although impacts modelled using specific climate models can exhibit non-linear trends over time with increases in impact indicators followed by decreases (or vice versa). In the 2050s time slice, the majority of impact indicators show larger differences in the magnitude of change between low-end (RCP2.6) and high-end (RCP8.5) scenarios than due to uncertainty from the selection of climate model, even though this uncertainty range increases compared to the 2020s. This highlights that uncertainty due to the RCP emission scenario begins to dominate over uncertainty due to the selection of climate models after the 2050s. This is contrary to the findings of Reyer et al. (2014) who found that the effects of using different climate models are more important than the choice of the emission scenario for simulating impacts on net primary productivity. This may be because we only applied three climate models per RCP in this study and deliberately selected these to encompass low/medium (for RCP2.6) or high-end (for RCP8.5) models. Hence, we are not capturing the full range of climate model uncertainty. Furthermore, Reyer et al. (2014) did not apply as high-end an emission scenario as RCP8.5, instead focusing on the older (and less extreme) SRES scenarios A1B and B1.

Who are the winners and losers under low-end and high-end climate change?

The varying spatial patterns of low-end and high-end climate change result in broad trends in winners and losers across

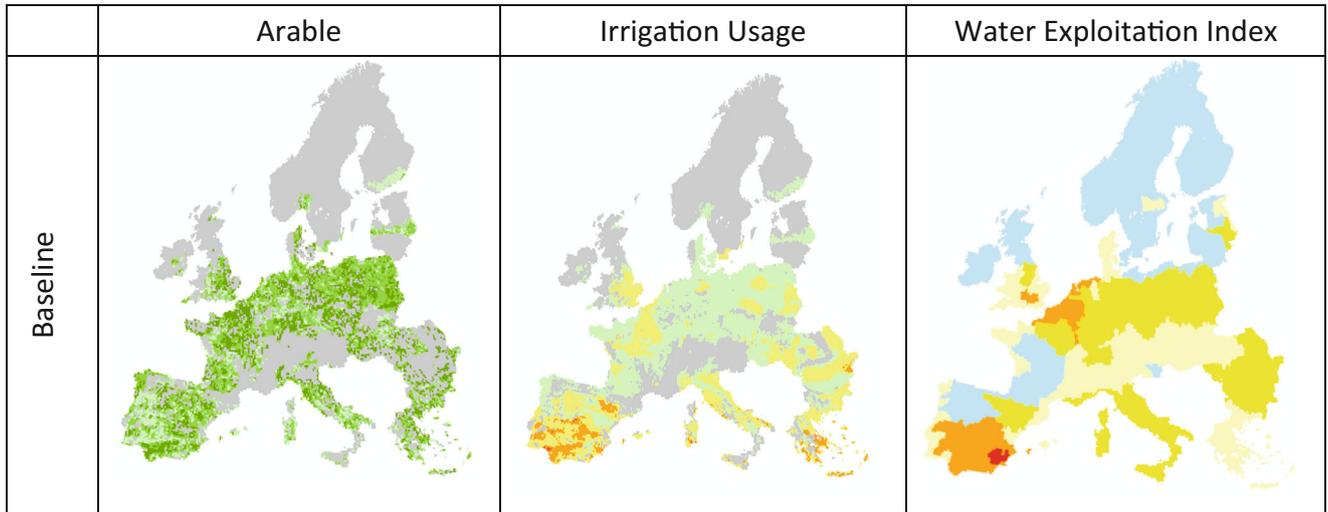
Fig. 3 Spatial patterns of impacts in arable land, irrigation usage and the water exploitation index at the 10'×10' gridded resolution under **a** baseline; **b** low-end (RCP2.6) and high-end (RCP8.5) climate-only scenarios for the 2080s; and **c** SSP1 socio-economic scenario combined with RCP2.6 and RCP8.5 climate scenarios; and SSP3 socio-economic scenario combined with RCP2.6 and RCP8.5 climate scenarios for the 2080s. Projections for RCP2.6 are based on the EC-EARTH/RC4A climate model and RCP8.5 on the CanESM2/CanRCM4 climate model (see Online Resource 4 for spatial patterns of impacts in land use)

Europe. Arable farming in the *Northern* region of Europe is the main winner under both low-end and high-end scenarios as higher temperatures increase the growing season and the options for growing a wider range of arable crops. However, this is projected to be at the expense of grassland farming systems. Increases in arable land and food production are also projected for the *Alpine* region under high-end climate scenarios with consequent decreases in grasslands and managed forest. *Northern* and *Alpine* regions of Europe are also the only regions where biodiversity vulnerability improves due to new climate and habitat space becoming available, although this should be interpreted with caution as it assumes the species are able to disperse quickly enough to access these new opportunities. Biodiversity is projected to lose in the *Southern*, *Continental* and *Atlantic* regions, as the suitable climate and habitat space for species moves northwards and eastwards.

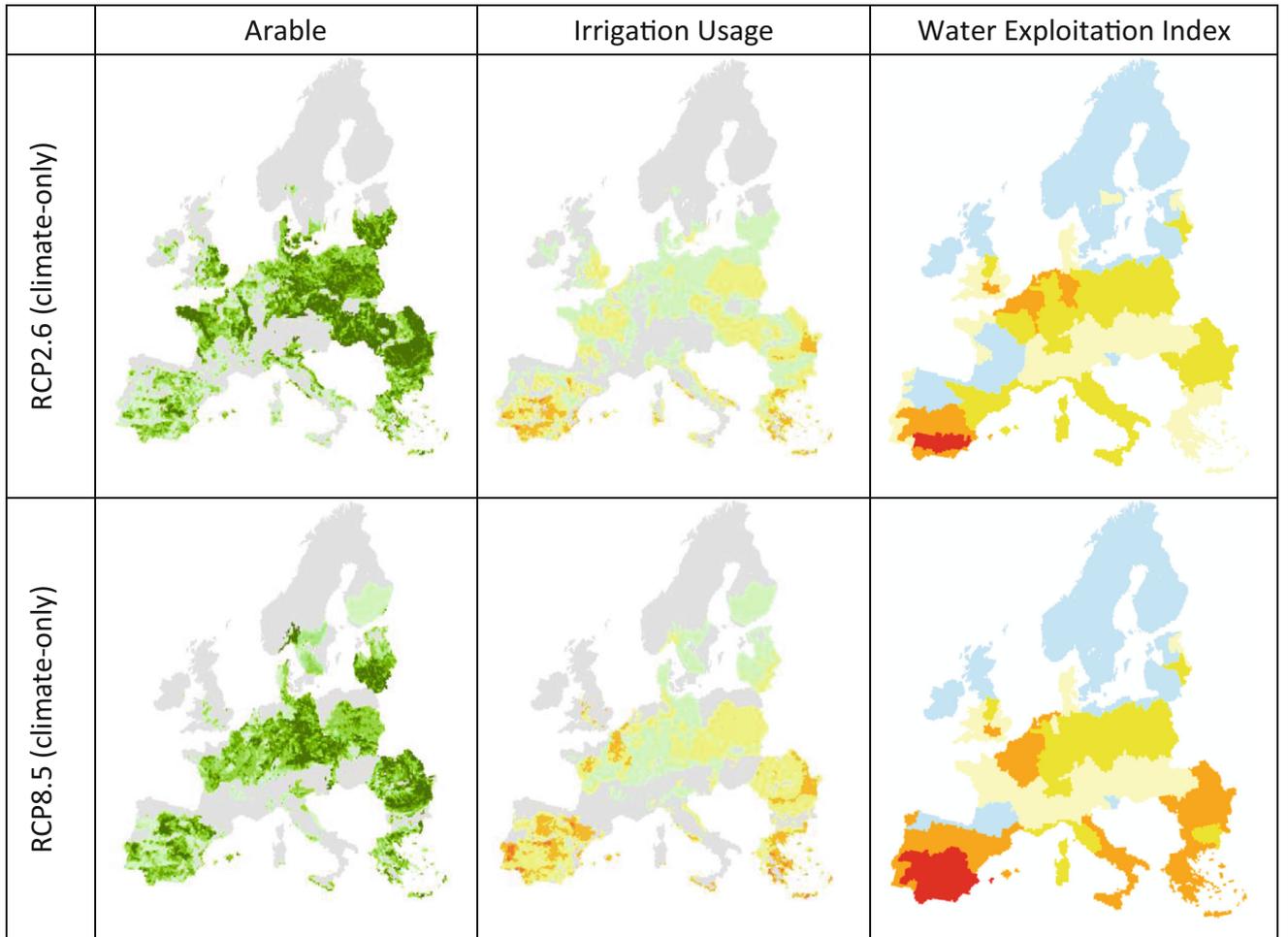
Intensive farmers in *Southern* and *Atlantic* regions of Europe lose as food production and arable land is projected to decrease under both low-end and high-end climate change due to more productive agriculture moving northwards where greater yields are possible per unit of land area. Productive grasslands are projected to slightly increase in these regions under low-end climate change, but to substantially decrease under high-end climate change being replaced by very extensive grasslands or unmanaged (abandoned) land. Irrigation increases in all regions under both low-end and high-end climate change as new arable areas expand their range of irrigated crops and existing areas require more irrigation to counteract higher evapotranspiration and in some areas lower precipitation. This leads to small increases in water stress in *Southern* Europe under low-end climate change and substantial increases under high-end climate change. Water stress also becomes an issue in river basins in *Continental* and *Atlantic* regions under high-end climate change. In addition to dealing with increasing water stress at certain times of the year, the water sector in the *Atlantic* region can also be considered a loser due to increases in the number of people flooded under both low-end and high-end climate change.

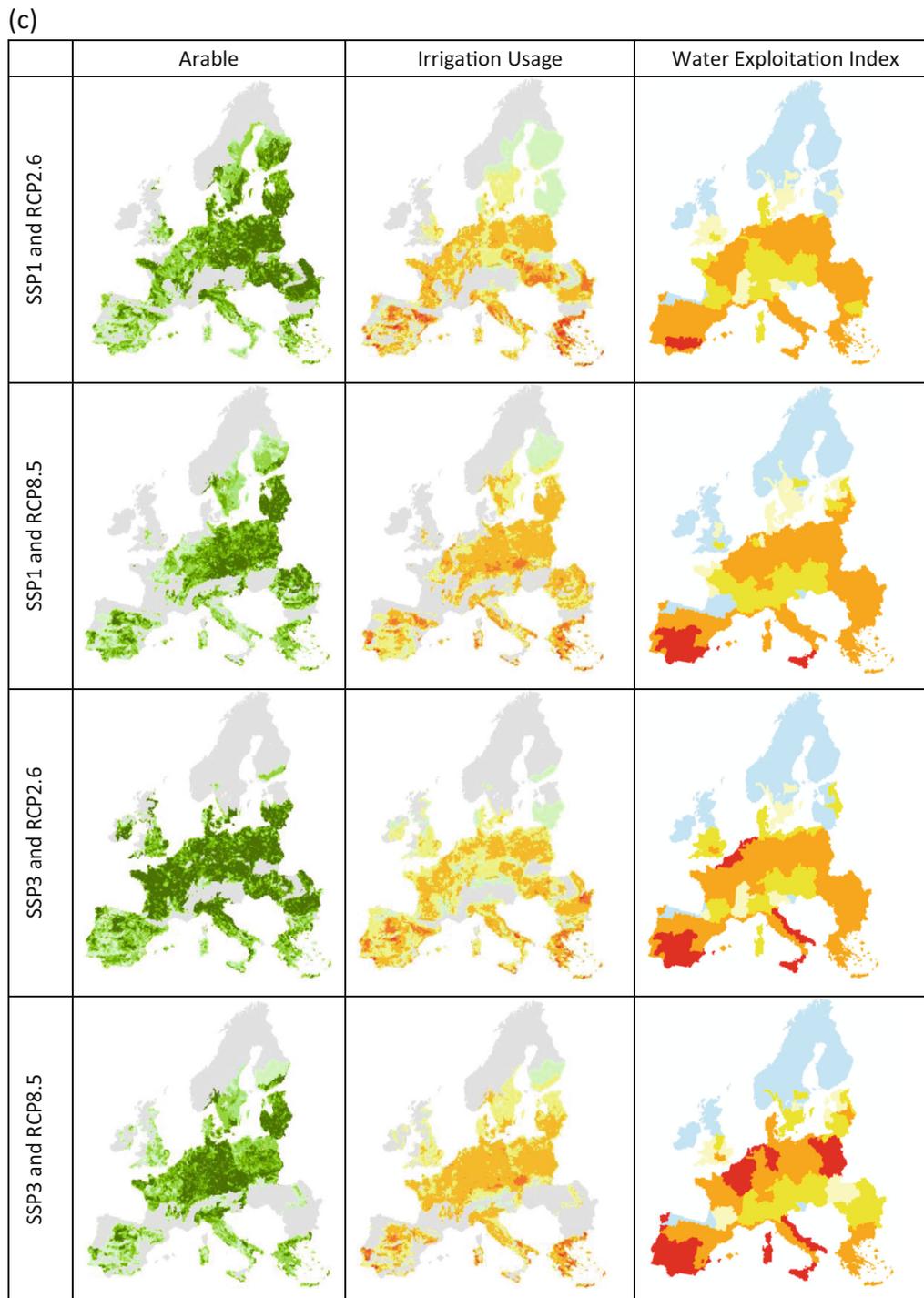
Managed forestry is the main sectoral loser, decreasing in *Southern* and *Continental* regions under low-end climate change and decreasing in all regions, except *Northern* Europe, under high-end climate change as the model assumes that tree species remain unchanged so they become highly stressed and unprofitable under the extreme changes in

(a)



(b)





	Arable	Irrigation Usage	Water Exploitation Index
Key	0.01 – 10%	0.01-10 mill m ³	WEI <= 0.1
	10-20%	10-50 mill m ³	WEI 0.1-0.2
	20-50%	50-100 mill m ³	WEI 0.2-0.4
	50-75%	100-200 mill m ³	WEI 0.4-1.0
	75-100%	Inten. agric. not irrigated	WEI > 1.0
		No intensive agriculture	

Fig. 3 (continued)

climate associated with RCP8.5. Nevertheless, carbon storage in forests increases under high-end climate change in all regions, except *Southern* Europe, due to large increases in unmanaged woodlands.

Similar regional impacts of climate change are reported in Dunford et al. (2015), EEA (2017), Iglesias and Garrote (2015) and Kovats et al. (2014). The main exception is that loss of biodiversity is also reported for mountain regions in many of these studies as they assume that existing species are lost and new species are unable to occupy northward and upward expansions in climate and habitat space. Reyer et al. (2014) also simulated increases in forest productivity in northern Europe, increases or decreases in central Europe and decreases in southern Europe. Ciscar et al. (2011) also found that scenarios with warmer temperatures and higher sea level rise result in more severe economic damage with the results being highly spatially variable across European regions. The authors concluded that southern Europe, the British Isles and northern central Europe appear most sensitive to climate change, whilst northern Europe is projected to have net economic benefits, driven mainly by the positive effects on agriculture.

These regional impacts are likely to lead to significant challenges for adaptation for the agricultural, forestry, water and nature conservation sectors. If the Paris Agreement targets are met incremental adoption of adaptation policies and practices may be sufficient to cope with the projected impacts. In contrast, under high-end climate change, conventional solutions to adaptation may prove not to be enough. Transformative solutions aimed at implementing radically different institutional arrangements, searching for synergies between adaptation and mitigation and linking them to sustainable development are likely to become increasingly important (Frantzeskaki et al. 2018, this issue; Gillard et al. 2016; Hermwille 2016; Tabara et al. 2018, this issue).

How do the challenges and winners/losers change under different socio-economic scenarios?

Including changes in socio-economic conditions results in much greater magnitudes of changes in the majority of impact indicators than climate change alone. Furthermore, there is considerably greater variation in the range and direction of change between the SSPs compared to that seen between the climate models and RCPs. Only three impact indicators show a consistent positive direction of change relative to baseline under all combined climate and socio-economic scenarios (irrigation usage, water exploitation index, urban land use), whilst only two impact indicators show a consistent negative direction of change (biodiversity, extensive grassland). All other indicators show a mixed direction of change depending on the assumptions within the socio-economic scenario.

This is particularly notable for land use change and how it affects food production with slight increases in the latter projected under SSP1 (6–7% with the range reflecting the difference between RCP2.6 and RCP8.5), large increases under SSP5 (60–61%) and moderate decreases under SSPs 3 and 4 (–16 to –11%). This shows how socio-economic factors much more strongly drive changes in land use and food production than changes in climate, sometimes overriding the differences due to low-end and high-end climate change. This is supported by Briner et al. (2012) who showed that land use change in Switzerland is highly dependent on the interactions between climatic and economic changes, which in turn affect food and timber production. Similarly, Holman et al. (2016) showed that the inclusion of socio-economic change with climate change reduced the certainty in direction of change of land and water impacts at national and sub-national scales in Scotland. The results demonstrate that European societal decisions are highly influential in determining the magnitude and direction of regional impacts of low-end and high-end climate change, with significant implications for both European regional inter-generational equity and adaptation responses (Holman et al. 2017).

Conclusions

This study has shown that impacts in multiple sectors in Europe differ significantly between low-end and high-end climate change scenarios after 2050. This leads to different “winners and losers” in terms of sectors and regions, with northern Europe gaining in agricultural productivity and potentially biodiversity, the Atlantic region losing in terms of flooding and intensive agriculture and southern Europe losing in terms of several sectoral indicators (agricultural and forest productivity, water stress and biodiversity vulnerability). The magnitude and direction of impacts differ considerably when socio-economic change is taken into account in addition to climate change. This highlights the importance of political and societal choices in determining the consequences of climate change. It also emphasises the need to consider climate change adaptation and mitigation actions together, particularly as studies have shown that impacts of the land-based mitigation strategies required to achieve low-end climate change consistent with the Paris Agreement are significant (Brown et al. 2017; Krause et al. 2017). Searching for an appropriate balance between adaptation and mitigation that takes account of cross-sectoral and inter-regional interdependencies will be essential for delivering a sustainable and resilient future for all citizens in Europe and globally.

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References

- Acosta-Michlik LA, Rounsevell MDA, Bakker M, Van Doorne A, Gómez Delgado M, Delgado M (2014) An agent-based assessment of land use and ecosystem changes in a traditional agricultural landscape of Portugal. *Intell Inf Manag* 6:55–80. <https://doi.org/10.4236/iim.2014.62008>
- Amell NW, Lloyd-Hughes B (2014) The global-scale impacts of climate change on water resources and flooding under new climate and socio-economic scenarios. *Clim Chang* 122(1–2):127–140. <https://doi.org/10.1007/s10584-013-0948-4>
- Audsley E, Trnka M, Sabaté S, Sanchez A (2015) Interactive modelling of land profitability to estimate European agricultural and forest land use under future scenarios of climate, socio-economics and adaptation. *Clim Chang* 128:215–227. <https://doi.org/10.1007/s10584-014-1164-6>
- Blanco V, Holzhauser S, Brown C, Lagergren F, Vulturius G, Lindeskog M, Rounsevell MDA (2017) The effect of forest owner decision-making, climatic change and societal demands on land-use change and ecosystem service provision in Sweden. *Ecosyst Serv* 23:174–208. <https://doi.org/10.1016/j.ecoser.2016.12.003>
- Briner S, Elkin C, Huber R, Gret-Regamy A (2012) Assessing the impacts of economic and climate changes on land-use in mountain regions: spatial dynamic modelling approach. *Agric Ecosyst Environ* 149:50–63. <https://doi.org/10.1016/j.agee.2011.12.011>
- Brown C, Alexander P, Holzhauser S, Rounsevell MDA (2017) Behavioural models of climate change adaptation and mitigation in land-based sectors. *Wiley Interdisciplinary Reviews: Climatic Change* 8(2):1757–7799, doi: <https://doi.org/10.1002/wcc.448>
- Bugmann H, Cordonnier T, Truhetz H, Lexer MJ (2017) Impacts of business-as-usual management on ecosystem services in European mountain ranges under climate change. *Reg Environ Chang* 17:3–16. <https://doi.org/10.1007/s10113-016-1074-4>
- Ciscar JC, Iglesias A, Feyen L, Szabó L, Van Regemorter D, Amelung B, Nicholl R, Watkiss P, Christensen OB, Dankers R, Garrote L, Goodess CM, Hunt A, Moreno A, Richards J, Soria A (2011) Physical and economic consequences of climate change in Europe. *Proc Natl Acad Sci* 108(7):2678–2683. <https://doi.org/10.1073/pnas.1011612108>
- Dunford R, Smith A, Harrison PA, Hangau D (2015) Ecosystem service provision in a changing Europe: adapting to the impacts of combined climate and socio-economic change. *Landsc Ecol* 30:443–461. <https://doi.org/10.1007/s10980-014-0148-2>
- EEA (2017) Climate change, impacts and vulnerability in Europe 2016. European Environmental Agency, Publications Office of the European Union, Luxembourg. doi: <https://doi.org/10.2800/534806> <https://www.eea.europa.eu/publications/climate-change-impacts-and-vulnerability-2016>
- Feyen L, Dankers R, Bódis K, Salamon P, Barredo JI (2012) Fluvial flood risk in Europe in present and future climates. *Clim Chang* 112:47–62. <https://doi.org/10.1007/s10584-011-0339-7>
- Frantzeskaki N, Hölscher K, Holman IP, Pedde S, Jäger J, Kok K, Harrison PA (2018) Transition pathways to sustainability in greater than 2°C climate futures of Europe. *Regional Environmental Change*, this issue
- Friedlingstein P, Andrew RM, Rogelj J, Peters GP, Canadell JG, Knutti R, Luderer G, Raupach MR, Schaeffer M, van Vuuren DP, Le Quéré C (2014) Persistent growth of CO₂ emissions and implications for reaching climate targets. *Nat Geosci* 7(10):709–715. <https://doi.org/10.1038/NGEO2248>
- Fuss S, Canadell JG, Peters GP, Tavoni M, Andrew RM, Ciais P, Jackson RB, Jones CD, Kraxner F, Nakicenovic N, Le Quéré C, Raupach MR, Sharifi A, Smith P, Yamagata Y (2014) Betting on negative emissions. *Nat Clim Chang* 4(10):850–853. <https://doi.org/10.1038/nclimate2392>
- Gillard R, Gouldson A, Paavola J, van Alstine J (2016) Transformational responses to climate change: beyond a systems perspective of social change in mitigation and adaptation. *WIREs Clim Change* 7(6): 251–265. <https://doi.org/10.1002/wcc.384>
- Hansen J, Sato M, Ruedy R, Schmidt GA, Lo K (2016) Global temperature in 2015. GISS, NASA, New York. Available from http://mahb.stanford.edu/wp-content/uploads/2016/01/20160120_Temperature2015.pdf
- Harrison PA, Holman IP, Cojocar 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. *Reg Environ Chang* 13(4): 761–780
- Harrison PA, Dunford R, Savin C-M, Rounsevell MDA, Holman IP, Kebede AS, Stuch B (2015a) Cross-sectoral impacts of climate change and socio-economic change for multiple European land- and water-based sectors. *Clim Chang* 128:279–292. <https://doi.org/10.1007/s10584-014-1239-4>
- Harrison PA, Holman IP, Berry PM (2015b) Assessing cross-sectoral climate change impacts, vulnerability and adaptation: an introduction to the CLIMSAVE project. *Clim Chang* 128:153–167. <https://doi.org/10.1007/s10584-015-1324-3>
- Harrison PA, Dunford RW, Holman IP, Rounsevell MDA (2016) Climate change impact modelling needs to include cross-sectoral interactions. *Nat Clim Chang* 6(9):885–890
- Hawkins E, Sutton R (2009) The potential to narrow uncertainty in regional climate predictions. *Bull Am Meteorol Soc* 90(8):1095–1107. <https://doi.org/10.1175/2009BAMS2607.1>
- Hawkins E, Ortega P, Suckling E, Schurer A, Hegerl G, Jones P, Joshi M, Osborn TJ, Masson-Delmotte V, Mignot J, Thorne P, van Oldenborgh GJ (2017) Estimating changes in global temperature since the pre-industrial period. *Bull Am Meteorol Soc* 98:1841–1856. <https://doi.org/10.1175/BAMS-D-16-0007.1>
- Hermwille L (2016) Climate change as a transformation challenge: a new climate policy paradigm? *Gaia* 25(1):19–22. <https://doi.org/10.14512/gaia.25.1.6>
- Hirabayashi Y, Mahendran R, Koirala S, Konoshima L, Yamazaki D, Watanabe S, Kim H, Kanae S (2013) Global flood risk under climate change. *Nat Clim Chang* 3(9):816–821. <https://doi.org/10.1038/NCLIMATE1911>
- Holman IP, Harrison PA, Metzger M (2016) Cross-sectoral impacts of climate and socio-economic change in Scotland—implications for adaptation policy. *Reg Environ Chang* 16:97–109. <https://doi.org/10.1007/s10113-014-0679-8>
- Holman I, Brown C, Janes V, Sanders D (2017) Can we be certain about future land use change in Europe? A multi-scenario, integrated-assessment analysis. *Agric Syst* 151:126–135. <https://doi.org/10.1016/j.agsy.2016.12.001>

- Holzhauser S, Brown C, Rounsevell M (2018) Modelling dynamic effect of multi-scale institutions on land use change. *Regional Environmental Change*, this issue
- Iglesias A, Garrote L (2015) Adaptation strategies for agricultural water management under climate change in Europe. *Agric Water Manag* 155:113–124. <https://doi.org/10.1016/j.agwat.2015.03.014>
- IPCC (2014) Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds)]. IPCC, Geneva
- Kok K, Pedde S, Gramberger M, Harrison PA, Holman IP (2018) New European socio-economic scenarios for climate change research: operationalising concepts to extend the shared socioeconomic pathways. *Regional Environmental Change*, this issue
- Kosaka Y, Xie S-P (2016) The tropical Pacific as a key pacemaker of the variable rates of global warming. *Nat Geosci* 9:669–674. <https://doi.org/10.1038/NGEO2770>
- Kovats S, Valentini R, Bouwer LM, Georgopoulou E, Jacob D, Martin E, Rounsevell M, Soussana J-F (2014) IPCC 5th Assessment Report Chapter 23, Europe, https://ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap23_FINAL.pdf
- Krause A, Pugh TAM, Bayer A, Doelman JC, Humpenöder F, Anthoni P, Olin S, Bodirsky BL, Popp A, Stehfest E, Armeth A (2017) Global consequences of afforestation and bioenergy cultivation on ecosystem service indicators. *Biogeosciences* 14:4829–4850. <https://doi.org/10.5194/bg-14-4829-2017>
- Madsen MS, Maule CF, Christensen JH, Fronzek F, Carter T (2016) IMPRESSIONS Climate Scenarios. Deliverable D2.3 of the EU-funded IMPRESSIONS project, <http://www.impressions-project.eu/documents/1/>
- Markovic D, Carrizo S, Freyhof J, Cid N, Lengyel S, Scholz M, Kasperdius H, Darwall W (2014) Europe's freshwater biodiversity under climate change: distribution shifts and conservation needs. *Divers Distrib* 20:1097–1107. <https://doi.org/10.1111/ddi.12232>
- Met Office (2015) Global climate in context as the world approaches 1°C above pre-industrial for the first time, United Kingdom Met Office, Exeter, <https://www.metoffice.gov.uk/binaries/content/assets/mohippo/pdf/7/6/onedegree2015.pdf>
- Mina M, Bugmann H, Cardonnet T, Irauschek F, Klopčič M, Pardos M, Caillieret M (2017) Future ecosystem services from European mountain forests under climate change. *J Appl Ecol* 54:389–401. <https://doi.org/10.1111/1365-2664.12772>
- Molina-Navarro E, Trolle D, Martínez-Pérez S, Sastre-Merlín A, Jeppesen E (2014) Hydrological and water quality impact assessment of a Mediterranean limno-reservoir under climate change and land use management scenarios. *J Hydrol* 509:354–366. <https://doi.org/10.1016/j.jhydrol.2013.11.053>
- Moore FC, Lobell DB (2014) Adaptation potential of European agriculture in response to climate change. *Nat Clim Chang* 4:610–614. <https://doi.org/10.1038/nclimate2228>
- Murray-Rust D, Rieser V, Robinson DT, Milicic V, Rounsevell MDA (2013) Agent-based modelling of land use dynamics and residential quality of life for future scenarios. *Environ Model Softw* 46:75–89. <https://doi.org/10.1016/j.envsoft.2013.02.011>
- Neumann B, Vafeidis AT, Zimmermann J, Nicholls RJ (2015) Future coastal population growth and exposure to sea-level rise and coastal flooding—a global assessment. *PLoS One* 10:e0118571. <https://doi.org/10.1371/journal.pone.0118571>
- New M, Lister D, Hulme M, Makin I (2002) A high resolution data set of surface climate over global land areas. *Clim Res* 21:1–25
- O'Neill BC, Kriegler E, Ebi KL, Kemp-Benedict E, Riahi K, Rothman DS, van Ruijven BJ, van Vuuren DP, Birkmann J, Kok K, Levy M, Solecki W (2017) The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob Environ Chang* 42:169–180
- Pedde S, Kok K, Onigkeit J, Brown C, Holman IP, Harrison PA (2018) Bridging uncertainty concepts across narratives and simulations in environmental scenarios. *Regional Environmental Change*, this issue
- Prudhomme C, Giuntoli I, Robinson EL, Clark DB, Arnell NW, Dankers R, Fekete BM, Franssen W, Gerteng D, Goslingh SN, Hagemann S, Hannab DM, Kimj H, Masakik Y, Satohl Y, Stackel T, Wadam Y, Wissem D (2014) Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment. *Proc Natl Acad Sci* 111(9):3262–3267. <https://doi.org/10.1073/pnas.1222473110>
- Ramsbottom D, Sayers P, Panzeri M (2012) Climate change risk assessment for the floods and coastal erosion sector. Defra Project Code GA0204. Report to Defra, London, UK, available from: <http://www.defra.gov.uk/environment/climate/government/>
- Reyer C, Lasch-Born P, Suckow F, Gutsch M, Murawski A, Pilz T (2014) Projections of regional changes in forest net primary productivity for different tree species in Europe driven by climate change and carbon dioxide. *Ann For Sci* 71(2):211–225. <https://doi.org/10.1007/s13595-013-0306-8>
- Rogelj J, Den Elzen M, Höhne N, Fransen T, Fekete H, Winkler H, Schaeffer R, Sha F, Riahi K, Meinshausen M (2016) Paris Agreement climate proposals need a boost to keep warming well below 2°C. *Nature* 534(7609):631–639. <https://doi.org/10.1038/nature18307>
- Sanderson BM, Xu Y, Tebaldi C, Wehner M, O'Neill B, Jahn A, Pendergrass AG, Lehner F, Strand WG, Lin L, Knutti R, Lamarque JF (2017) Community climate simulations to assess avoided impacts in 1.5 and 2°C futures. *Earth Syst Dyn* 8:827–847. <https://doi.org/10.5194/esd-8-827-2017>
- Tàbara D, Jäger J, Mangalagiu D, Grasso M (2018, this issue) Defining transformative climate science to address high-end climate change. *Reg Environ Chang* doi: <https://doi.org/10.1007/s10113-018-1288-8>
- Thom D, Rammer W, Dimböck T, Müller J, Kobler J, Katzensteiner K, Helm N, Seidl R (2017) The impacts of climate change and disturbance on spatio-temporal trajectories of biodiversity in a temperate forest landscape. *J Appl Ecol* 54:28–38. <https://doi.org/10.1111/1365-2664.12644>
- Trnka M, Rötter RP, Ruiz-Ramos M, Kersebaum KC, Olesen JE, Žalud Z, Semenov MA (2014) Adverse weather conditions for European wheat production will become more frequent with climate change. *Nat Clim Chang* 4:637–643. <https://doi.org/10.1038/nclimate2242>
- van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V, Lamarque JF, Masui T, Meinshausen M, Nakicenovic N, Smith SJ, Rose SK (2011) The representative concentration pathways: an overview. *Clim Chang* 109:5–31. <https://doi.org/10.1007/s10584-011-0148-z>
- Wimmer F, Audsley E, Savin C-M, Malsy M, Dunford R, Harrison PA, Schaldach R, Flörke M (2015) Modelling the effects of cross-sectoral water allocation schemes in Europe. *Clim Chang* 128: 229–244. <https://doi.org/10.1007/s10584-014-1161-9>