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Trade-offs are unavoidable in multi-objective adaptation even in a post-Paris Agreement world

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Abstract

In a post-Paris Agreement world, where global warming has been limited to 1.5 or 2ºC, adaptation is still needed to address the impacts of climate change. To reinforce the links between such climate actions and sustainable development, adaptation responses should be aligned with goals of environmental conservation, economic development and societal wellbeing. This paper uses a multi-sectoral integrated modelling platform to evaluate the impacts of a +1.5ºC world to the end of the 21st century under alternative Shared Socioeconomic Pathways (SSPs) for Europe. It evaluates the ability of adaptation strategies to concurrently improve a range of indicators, relating to sustainable development, under the constraints imposed by the contrasting SSPs. The spatial synergies and trade-offs between sustainable development indicators (SDIs) are also evaluated across Europe. We find that considerable impacts are present even under low-end climate change, affecting especially biodiversity. Even when the SDIs improve with adaptation, residual impacts of climate change affect all the SDIs, apart from sustainable production. All but one of the adaptation strategies have unintended consequences on one or multiple SDIs, although these differ substantially between strategies, regions and socio-economic scenarios. The exception was the strategy to increase social and human capital. Other strategies that lead to successful adaptation with limited unintended consequences are those aiming at adoption of sustainable behaviours and implementation of sustainable water management. This work stresses the continuing importance of adaptation even under 1.5ºC or 2ºC of global warming. Further, it demonstrates the need for policy-makers to develop holistic adaptation strategies that take account of the synergies and trade-offs between sectoral adaptation strategies, sectors and regions, and are also constrained by scenario context to avoid over-optimistic assessments.

1. Introduction

In a future post-Paris Agreement world, where the aim to limit global warming to 1.5 or 2ºC to significantly reduce the risks and impacts of climate change has been achieved, adaptation actions will still be needed to address the impacts of these lower levels of warming together with the impacts of socio-economic changes (Harrison et al., 2018; Jacob et al., 2018). To reach the Paris Agreement target, climate mitigation policies, such as those defined in individual countries Nationally Determined Contributions, need to be updated and significantly enhanced with stricter regulations (Michaelowa et al., 2018) and fast and extensive technological advances across the energy, manufacturing, infrastructure, forestry and agricultural sectors are required (Kuramochi et al., 2018). These enhanced climate mitigation actions, together with continuing changes in non-climate drivers such as social, economic and political changes (O'Neill et al 2017), will impose many constraints on land use and society (Berry et al., 2015; Ingwersen et al., 2014) through actions related to land-based mitigation and societal transformation towards more sustainable behaviours. These factors may inadvertently impose constraints that affect the adaptive capacity of sectors and society to future environmental changes. Thus, the design and implementation of effective adaptation strategies should take into account their long-term resilience to both climate and socio-economic changes.

A "roadmap" guiding the direction in which climate change adaptation responses, alongside mitigation responses, need to move is provided by the principles of sustainable development and multiple, diverse societal targets such as the Sustainable Development Goals (SDGs) (United Nations, 2016), the Aichi Biodiversity Targets (CBD, 2010) and the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015). The challenging objectives set by the SDGs and the Paris Agreement provide a common ground where the links between climate actions and sustainable development across the social, economic and environmental pillars can be positively reinforced (Gomez-Echeverri, 2018).

The multi-dimensionality of climate adaptation goals calls for integrated assessments that consider the different components of the human - environment system and their interactions (Tavoni and Levin, 2014; Verburg et al., 2016). Harrison et al. (2016) demonstrated that excluding cross-sectoral interactions hinders the ability to accurately understand the magnitude, direction and spatial pattern of impacts. This especially affects the water and food production sectors, due to their inter-connectedness to other sectors that compete for the use of the same finite land and water resources. Furthermore, Collste et al. (2017) and Mainali et al. (2018) showed that integrated approaches better highlight the synergies and trade-offs between different sectoral adaptation goals. Identifying the linkages between cross-sectoral goals can lead to stronger synergies (Mainali et al., 2018), while utilising the identified synergies leads to systemic improvements that favour the achievement of the goals (Collste et al., 2017). Moreover, indicators, relating the examined sector to a measurable variable derived based on scientific judgment (Pedro-Monzonís et al., 2015), are a useful tool to use in integrated assessments for capturing sectoral and cross-sectoral climate impacts, which is key to providing policy makers with robust findings to support decision making (von Stechow et al., 2016).

Adaptation responses and strategies are not immune from the socio-economic context, due to the limitations of, and variability in, the capacity of different actors to adapt. This arises from the influence of available economic and natural resources, social networks, entitlements, institutions and governance, human resources, knowledge and technology on all levels of society, from decision-makers and industries to individuals (Azhoni et al., 2017; Brooks et al., 2005; Dunford et al., 2014; Moser and Ekstrom, 2010; Schneider et al., 2000). These determinants of adaptive and coping capacity will be modified by the future evolution of socio-economic conditions at all scales from the global (e.g. O'Neill et al., 2017), to the regional and national (e.g. Kok et al., 2018; Tinch et al., 2015).

It is thus important that studies aiming to assess the outcomes of adaptation strategies employ approaches that account for the cross-sectoral feedbacks, constraints and their differing importance within alternative socio-economic futures (Rosenzweig et al., 2017; Schellnhuber et al., 2014). However, very few models and studies incorporate all the above factors in their framework (Holman et al., 2018). One exception is the CLIMSAVE Integrated Assessment Platform or IAP (Harrison et al., 2015b), which has been used in a number of cross-sectoral impact and adaptation studies (e.g. Dunford et al., 2014, 2015; Harrison et al., 2016, 2015a; Holman et al., 2017; Jäger et al., 2014), and, its successor, the IMPRESSIONS IAP2 (Harrison et al., 2018; Holman et al., 2017), which we utilise in this study.

In this paper, we use a multi-sectoral integrated modelling platform to evaluate the ability of different adaptation strategies to concurrently improve a range of sustainable development-related indicators, accounting for the constraints imposed by contrasting alternative socio-economic futures. We focus on Europe at the end of the 21st century under the lowest representative concentration pathway (RCP2.6, Moss et al., 2010; van Vuuren et al., 2007), -which is broadly consistent with global warming associated with the Paris Agreement. There are three main objectives for the study. Firstly, to understand the impacts of lower-end climate change on a range of multi-sectoral indicators under alternative European socio-economic futures. Secondly, to evaluate the efficacy of a set of adaptation strategies and the consequent synergies and trade-offs between the indicators across Europe to identify sectoral 'winners' and 'losers'. And thirdly, to discuss the implications of spatial variations in the trade-offs between indicators from an understanding of the underlying mechanisms of the strategies, with the aim of designing more effective adaptation strategies that minimise unintended consequences.

2. Methods

2.1. The IMPRESSIONS Integrated Assessment Platform 2 (IAP2)

The IAP2 is an interactive, web-based, cross-sectoral modelling platform developed within the IMPRESSIONS[1] project. IAP2 includes interlinked meta-models for a number of sectors including urban development, agriculture, forestry, water provision, coastal and fluvial flooding and biodiversity. It is a recent development of the widely published CLIMSAVE IAP (e.g. Harrison et al., 20153a, 2016; Holman et al., 2017; Kebede et al., 2015) with the inclusion of regional climate change scenarios from multiple GCM-RCMs using the Representative Concentration Pathways (RCP) and European versions of the Shared Socioeconomic Pathways (SSPs) as inputs to the modelling system. The evaluation of the underlying models within the two versions of the platforms has been extensively published, including with sensitivity (IAP1: Kebede et al., (2015); IAP2: Fronzek et al., (2019)) and uncertainty (Brown et al., 2015; Dunford et al., 2015) analyses and comparative performance of stand-alone and integrated model application (Harrison et al., 2016). The IAP2 results are presented at a 10' by 10' (approximately 16 km × 16 km) grid-cell resolution for the European Union (including the UK), Norway and Switzerland. Baseline simulations are based on 1961–1990 for climate

[1] Impacts and risks from high-end scenarios: Strategies for innovative solutions http://www.impressions-project.eu/

variables, and 2010 for socio-economic variables. A brief description of the main models is given below:

- Urban expansion is simulated as a function of the scenario values of population, GDP, household preference for proximity to green space versus social amenities, attractiveness of the coast (scenic value versus flood risk) and strictness of the planning regulations to limit sprawl. Development in urban and rural areas is given first priority in the allocation of land;
- Flood impacts are based on topography, relative sea-level rise or change in simulated peak river flow and the estimated Standard of Protection of flood defences. The probability of flood inundation constrains the suitability of floodplain land for agriculture;
- Water resources are simulated at a large river basin scale, with the difference between simulated total water availability (driven by climate) and projected non-agricultural (domestic, industrial and energy) water consumption and environmental allocation in each spatial unit determining the maximum availability for agricultural irrigation;
- Forest species are simulated to assess potential average annual timber yields and Net Primary Production (NPP) for a range of deciduous and coniferous tree species under different management regimes across Europe;
- Crop yields are simulated for a range of annual and permanent crops (winter and spring wheat, barley and oilseed rape, potatoes, maize, sunflower, soya, cotton, grass and olives) under rainfed and irrigated conditions across Europe;
- Rural land allocation for agriculture and forestry is based on constrained profit maximisation (based on simulated crop and timber yields, scenario production costs and prices), taking account of land availability (including constraints due to urbanisation, soils and flood risk) and maximum irrigation availability, the simulated

yields of each of the crops and tree species and the demand for food and timber within the scenario. The model aims to meet the demand for food and timber within Europe (as a function of population, GDP, net imports, dietary preferences and bioenergy demand) through iterating crop and timber prices to expand or contract agricultural and managed forest areas. Land is allocated to the land use types according to relative profit until demand for each commodity (cereals, oilseeds, proteins, meat, dairy, fibres and timber) is met, in the order of decreasing profitability of intensive (arable) agriculture, intensive (dairy) agriculture, extensive (sheep and beef) agriculture, very extensive (sheep) agriculture and managed forests. Any remaining land is not used for productive purposes, and is allocated to either unmanaged forest (if NPP is sufficient for establishment and growth through natural succession) or unmanaged land.

- Species distributions are simulated for 91 species of plants, animals, birds and insects that are representative of the broad range of habitats from coasts to mountains, according to each species' climate suitability. The availability of both suitable climate and habitat (from the rural land allocation outputs and soil types) determines potential future distributions.

Further detailed information on the IAP2 is available in Holman et al. (2017a, 2011 for IAP2 and 1, respectively).

2.2. Scenarios

2.2.1. Climate

A sub-set of three climate model simulations were selected from the fifth phase of the Coupled Model Intercomparison Project (CMIP5-Taylor et al., 2012), dynamically downscaled for the European CORDEX domain (Jacob et al., 2014). In order to represent levels of warming compatible with the Paris Agreement, the model selection was based on the availability of downscaled projections following the lower-end RCP2.6 emission scenario, that project warming levels of less than 1.5ºC at the end of the 21st century compared to the pre-industrial period (Holman et al., 2017). GCM simulations were bias-adjusted against the CRU TS3.1 monthly mean data using the Delta Change method (Madsen et al., 2016). Information on the selected models is summarized in Table 1.

The time period from 1961 to 1990 is considered as the climate baseline, while the end of 21st century time-slice (2071 to 2100) is the focus of the climate projections for the present analysis. This time period will be referred to as the 2080s.

Table 1. Summary of the GCM-RCMs used in this study. All GCMs are based on the RCP2.6 emissions scenario. Change in average annual temperature (ΔT) and precipitation (ΔPr) is calculated for the European region for 2071-2100, relative to 1961-1990.

GCM	RCM	ΔT [ºC]	ΔPr [%]
EC-Earth	RCA4	1.4	4
MPI-ESM	REMO	1.3	1
NorESM1-M	RCA4	1.3	4

2.2.2. Socio-economics

The socio-economic scenarios, the "European Shared Socio-economic Pathways" (Eur-SSPs), were developed as equivalent scenarios (according to the interconnectedness levels of Zurek and Henrichs, 2007) to the global SSPs of O'Neil et al. (2014) as part of the IMPRESSIONS project. Through an expert-driven process described in Kok et al. (2018), the global SSPs were mapped onto the stakeholder-developed European scenarios of Kok et al. (2015); which were extended from the 2050s to 2100 informed by the global SSPs. Trends and quantification of key model parameters were then estimated for the new Eur-SSPs to facilitate their use as model input (Pedde et al., 2018). Kok et al. (2018) describes the full European SSPs, but these are summarised below and in Supplementary Table 1:

- Eur-SSP1 (We are the World) - a strong commitment to achieve sustainable development goals is achieved through effective governments and global cooperation, that ultimately results in less inequality and less resource intensive lifestyles.
- Eur-SSP3 (Icarus) - economic shocks in major economies and regional conflicts lead to increased antagonism between and within regional blocks that result in the disintegration of European social fabric and many European countries struggling to maintain living standards.
- Eur-SSP4 (Riders on the Storm) - power becomes concentrated in a political and business elite, which is accompanied by increasing disparities in economic opportunity that results in a substantial proportion of Europe's population having a low level of development.
- Eur-SSP5 (Fossil-fuelled Development) - increasing faith in competitive markets, innovation and participatory societies produces rapid technological progress and development of human capital, but is accompanied by a lack of environmental concern and exploitation of fossil fuels.

Representative model input parameters used to characterise the different Eur-SSPs along with their changes per Eur-SSP compared to baseline are shown in Table 2. For simplicity, the developed Eur-SSPs will be referred to hereafter in the text as SSPs.

Table 2. Selected parameters of the European socio-economics scenarios used in IAP2. The changes in the quantitative parameters' state are for the 2080s compared to the baseline period.

		SSP1	SSP3	SSP4	SSP5
Quantitative	Population change	No change	-38%	-22%	+47%
	Net food imports	-12.5%	-5.3%	+4.3%	+17.7%
	GDP	+259%	+48%	+200%	+724%
	Beef and lamb consumption	-82%	No change	No change	+53%
	Chicken and pork consumption	-34%	+35%	+35%	+74%
Qualitative	Technology development & transfer	Rapid	Slow	High in high-tech economies and sectors; slow in others with little transfer	Rapid
	Carbon (energy) intensity	Low	High	Low/Medium	High
	Environmental status	Improving condition	Serious degradation	Highly managed near high-income	Highly engineered approaches

				areas; degraded otherwise	
	Human capital	High	Low/Medium	No change	High
	Social capital	High	No change	No change	High
	Financial capital	Medium/High	Low	High	Medium/High
	Manufactured capital	Medium/High	Low/Medium	Medium/High	Medium/High

2.3. Adaptation strategies

Eight different strategies to adapt to climate and socio-economic changes were considered, similar to the approach of Dunford et al. (2015). Strategies aim to achieve climate resilience while pursuing a range of goals relating to sustainable development, by specifically targeting and investing in water, forestry, environment, flood protection, behavioural changes, society, bioenergy and food production. The adaptation strategies were applied within the SSPs through changing the socio-economic inputs to the IAP2.

The differing capacity to adapt between the SSPs are reflected in scenario-specific adaptation limits to the numerical model inputs in the IAP2. These limits are prescribed as a function of:

- the unconstrained range of input values that are plausible and consistent with the underlying socio-economic scenario storyline;
- the consistency between the broad type of adaptation (human, technological, financial etc.) and the scenario narrative, i.e. behavioural adaptation would be expected to be more effective in an SSP such as SSP1 characterised by high human and social capital; and

- the availability of the most limiting capital (human, social, manufactured or financial) within the SSP for the given adaptation.

Each adaptation strategy was implemented by changing the model inputs to the adaptation limit (maximum or minimum) within the above scenario constraints.

To assess the efficacy of the strategies, a "No action" strategy is also considered (Strategy0) which expresses the impacts of the combined climate and socio-economic changes without any planned adaptation actions. A description of the adaptation strategies, and the model settings used to implement them in IAP2, are shown in Table 3.

Table 3. Adaptation strategies applied within each combination of climate model and socio-economic scenario.

No.	Adaptation strategies [Target]	Description	Settings (↓decrease to scenario minimum; ↑increase to scenario maximum)
0	No action	No measures implemented	Default settings
1	Sustainable water management [Water]	Aiming to reduce water use and maximise environmental allocation of water	Water saving (technological)↑ Water saving (behavioural) ↑ Water demand prioritization = Environment Irrigation water price ↑
2	Maximising forest area [Forestry]	Increasing forest area (managed and unmanaged) through protection, expansion and facilitating agricultural land use conversion	Net Imports to Europe ↑ Tree species = ‘‘Optimum’’ (all regions) Forest management = unevenaged Protected Area change ↑ Protected Area that is Forest = 100 % Method for Protected Area allocation = “connectivity then Buffering” Arable conservation land ↑
3	Land-sharing [Environment]	Maximising “landscape” diversity and value for recreation: maintaining	Change in diet (red meat) ↑ Crop inputs ↓ Arable conservation land ↑

		and expanding less intensive land uses (agricultural and forestry) and minimising urban sprawl	Protected Area (PA) change ↑ [PA Forest] and [PA Agriculture] = 33%, 33% Method for Protected Area allocation = ‘‘Connectivity then buffering’’ Forest management = “Unevenaged” Spatial planning to control urban sprawl=High
4	Flood protection [Floods]	Minimising flooding impacts: avoiding coastal floodplain development and improvement flood protection	Preference for coastal living ↓ Standard of Protection of flood defences ↑
5	Sustainable behaviours [Behavioural changes]	Combining water savings to make water available for the environment, reduction in agricultural and forestry management intensity, and dietary change	Water saving (technological)↑ Water saving (behavioural) ↑ Water demand prioritization = Environment Crop inputs ↓ Change in diet (red meat) ↓ Change in diet (white meat) ↓ Net Imports to Europe ↓ Forest management = unevenaged
6	Human and social capital [Society]	Strategies to increase social and human capital	Social capital ↑ Human capital ↑

		and people-based flood resilience measures	Flood management (resilience)
7	Bioenergy [Energy]	Maximising bioenergy production: increasing biomass and biofuel production	Arable conservation land ↑ (farm woodland) Change in biofuel production ↑ Tree species = ‘‘Optimum’’ (all regions) Forest management = “Optimum” (all regions)
8	Agricultural intensification for land-sparing [Food]	Promoting domestic production of food through agronomic improvement, increased crop inputs, prioritising agricultural water use	Yield improvement ↑ Water demand prioritization = Food Irrigation efficiency ↑ Reducing diffuse pollution from agriculture ↓ Set-aside ↓ Agricultural mechanisation improvement↑

2.4. Sustainable development indicators

To assess the impacts of the climate and socio-economic scenarios and the efficacy of adaptation strategies, we used indicators relating to different aspects of sustainable development. These sustainable development indicators (hereafter, SDIs) were derived from different social, environmental and economic components of the IAP2 outputs to depict human-environment system interactions. Eight indicators within the three pillar framework of sustainable development (environment, economy and society) (Papadimitriou et al., 2019) were considered in total, each focussing specifically on flood protection, food security, water, bioenergy, employment, sustainable production, environment and biodiversity. The SDIs were calculated using direct or derived indicators from IAP2 outputs. The SDIs are summarised in Table 4 and a detailed description of their derivation based on the IAP2 outputs is provided in the ESM.

Table 4. Summary of SDIs used in this study.

SI	SDI focus	SDI description	SDI derivation
1	Floods	Vulnerability to flooding	Population present in areas with vulnerability to flooding
2	Food	Food security	Per capita calorific value of European food production
3	Water	Vulnerability to water over-exploitation	Population present in areas with vulnerability due to water over-exploitation
4	Bioenergy	Availability of biomass and biofuels	Tonnes of arable crop and managed timber production used for bioenergy
5	Employment	Agricultural and forestry employment	Employment based on standard labour requirements of agricultural and forest systems

6	Sustainable production	Sustainable agriculture	Food production per unit of input fertiliser usage
7	Environment	Total forest area	Sum of managed and unmanaged forest areas
8	Biodiversity	Species' presence	Number of species present, based on simulated bioclimatic and habitat suitability for 91 species, with agricultural set-aside land able to provide multiple climatically-appropriate habitats

The SDIs were evaluated for Europe and for five biogeographical European sub-regions (Alpine, Northern, Atlantic, Continental and Southern, shown in Figure 1) defined by Metzger et al. (2005), to examine spatial differences in adaptation effectiveness and trade-offs.

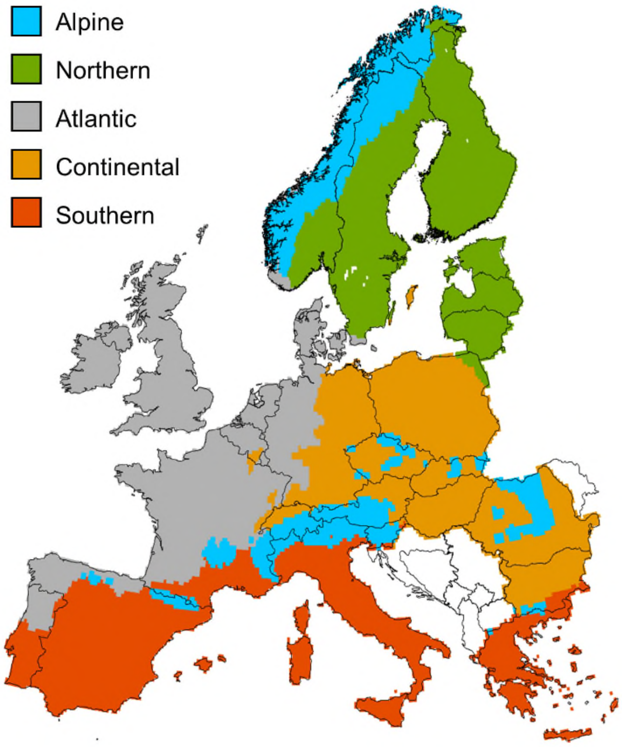

Figure 1. The IAP2 domain, split into European sub-regions, defined by Metzger et al., (2005). IAP2 has a 10' grid spatial resolution (~16 km grid).

2.5. Impacts and strategy efficacy

The impacts of climate and socio-economic change and the efficacy of adaptation strategies in improving the SDIs are expressed as the relative changes in the SDIs. Thus, the absolute state of each indicator in the baseline or future time-slice is not the focus for this study. Changes in the SDIs are expressed as fractions of the SDI value in the future time-slice over a reference SDI value. Expressing the differences in SDIs as fractions normalizes the results across different SDIs and regions, with values greater than 1 indicating improvements in the SDI state and values less than 1 indicating deteriorations. For the SDIs in which a reduction in their value is the positive outcome (SDIs 1 and 3, population vulnerable to flooding and water over-exploitation respectively), the abovementioned fractions are inverted, to provide a consistent comparison with the other SDIs.

Based on this framework, three types of effects are examined here. First, the effects of climate and socio-economic changes on an SDI compared to baseline conditions, under no action ($Strategy0_{SSPn}$/Baseline). Second, the efficacy of a strategy compared to no action, under climate and socio-economic changes ($StrategyX_{SSPn}$ /$Strategy0_{SSPn}$). And finally, the efficacy of a strategy with reference to the baseline conditions ($StrategyX_{SSPn}$ /Baseline).

3. Results

3.1. Impacts under low-end climate change in different socio-economic futures

The impacts of the climate and socio-economic scenarios on the examined SDIs in the 2080s compared to the baseline period are depicted in Figure 2. For the analysis we considered the ensemble mean of the results produced by the three climate models. Single model results are not presented as the variation in their projections of land use classes is small (Supplementary Table 2). Moreover, due to the spatial aggregation for the calculation of changes in SDIs, results from the different ensemble members fall into the same category of change (Supplementary Figure 1).

Low-end climate change (RCP2.6) and varying socio-economic changes are associated with both positive and negative effects on the examined SDIs, and these differ notably for the different SSPs (Figure 2). For example, the majority of the indicators (five out of eight) improve under SSP1 (flood protection, food, water, bioenergy and sustainable production), while only three out of eight show improvements under SSP5 (bioenergy, sustainable production and environment) when aggregated at the European scale. SSP3 and SSP4 both show improvements for four out of the eight indicators; food, water and biodiversity improve for both SSPs, whilst flood protection also improves in SSP3 and employment in SSP4. The SSP dependency of the impacts is also observed across the European sub-regions. For example, flood protection, food and water related SDIs improve for most sub-regions under SSP1 (four out of the five sub-regions for flood protection and food, and two out of five for water), while the same indicators deteriorate in all sub-regions under SSP3 and in the majority of sub-regions in SSP5 (flood protection deteriorates across all sub-regions, food for three out of five, and water for four out of five). Consistent responses across SSPs and regions are only found for sustainable production (positive effects) and biodiversity (negative effects) SDIs. This indicates that even low-end climate change is projected to impact biodiversity in a substantial manner, as the effects persist even under the most environmentally-friendly socio-economic scenario SSP1.

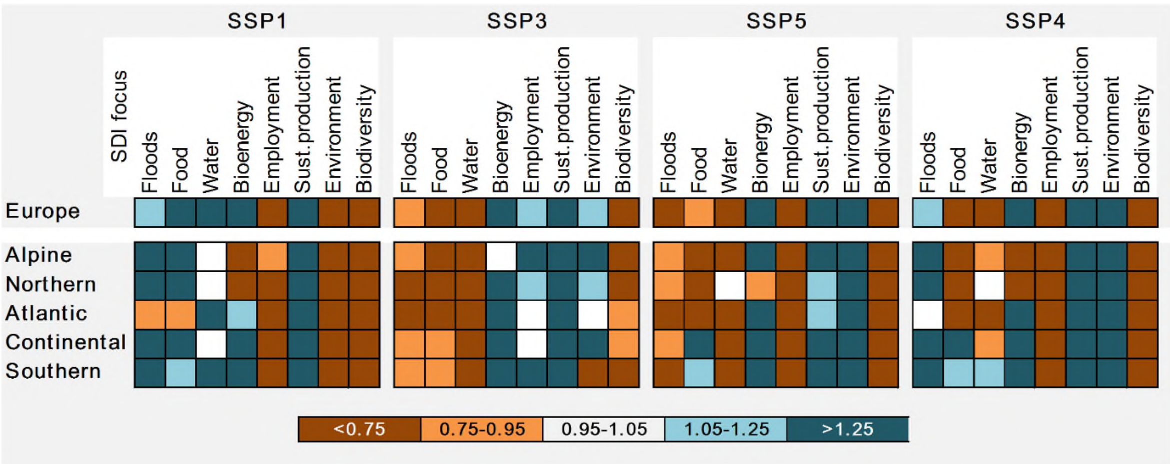

Figure 2. Climate and socio-economic impacts on the SDIs, at 2071-2100, calculated as proportions relative to baseline, for Europe and European sub-regions. Results are presented for different socio-economic scenarios (SSPs). Blue colour hues represent improvements in the SDIs and orange hues deteriorations.

Supplementary Figure 2 of the ESM shows the relative distribution of land use classes at the European level, for the baseline period and for the 2080s under the influence of different socio-economic scenarios. This information is important for understanding the differences in the SDI response between the SSPs. For example, under SSP1 there is a large reduction in the extent of forest areas compared to the baseline and other SSPs. This leads to declines in the environment SDI (which corresponds to total forest area) in SSP1, but increases for the other SSPs that result in increased forest coverage compared to the baseline period. Forest area reduction in SSP1 is caused by expansion of the agricultural (arable and grassland) land use classes, as a response of the model to the environmentally-friendly lower intensity agricultural production systems within SSP1 and the decreased food imports (to reduce environmental footprint) in the scenario, signifying that a greater component of the European food demand has to be covered by food grown within Europe. The expansion of agricultural areas in SSP1 in order to meet net food demand explains the improvement of the food SDI shown in Figure 2. Alternatively, the food SDI deteriorates under SSP3, a scenario of decreases in net food imports (although smaller compared to SSP1), decreased wealth (as expressed by Gross Domestic Product) and a decreased European population. In the case of SSP3, the overall decreased demand for food can be met with a small agricultural production area, so a larger proportion of the population are potentially vulnerable to food insecurity due to a reliance on less effective food distribution systems in this fragmented Europe.

3.2. Effect of adaptation strategy implementation

The effects of implementing each of the eight adaptation strategies within the context of the four SSPs combined with RCP2.6 on the SDIs for Europe and the five sub-regions are graphically summarised in Figure 3. The numeric values corresponding to the colour hues in Figure 3 are tabulated in Supplementary Table 3 of the ESM. The grey dots in the improving SDIs indicate that, after the strategy implementation, the SDI state is the same or better than at the baseline period.

Figure 3 reveals the complex cross-sectoral interactions associated with the different adaptation strategies, which results in various synergies and trade-offs across SDIs and regions. There is no single strategy that improves all the SDIs and unintended trade-offs are present in all the strategies for at least one SSP. For example, for Europe, strategy 1 (Sustainable water management) has positive effects for the water related SDI for all SSPs, for the environment SDI for SSP1, but negative impacts on employment for SSP4. For SSP1, the improved environment SDI can be attributed to increased agricultural productivity due to more effective water management and irrigation, which allows land use transitions to increase forest areas. For other SSPs this transition does not considerably affect the environment SDI as they already have higher forest coverage. In contrast, the reduction of agriculturally productive areas leads to the deterioration of the employment SDI in SSP4. Another representative example of the SSP dependency of the efficacy and trade-offs associated with the adaptation strategies is strategy 8 (Agricultural intensification for land-sparing) for Europe. In this case, the water, bioenergy and biodiversity SDIs only improve for SSP1 while they exhibit no change for the other SSPs (or even deteriorate in the case of the water SDI in SSP5 and the bioenergy SDI in SSP4). This is because SSP1 has such a shortage of land other than agriculture that land sparing makes a real difference by freeing up land for other land uses, such as forests (improved environment SDI) and habitats for different species (improved biodiversity SDI). The same logic explains the deterioration of the employment SDI under all the SSPs with strategy 8 (as agricultural areas have a higher relative employment requirement than managed forest).

Strategy 5 (Sustainable behaviours) improves two SDIs (water and sustainability) for SSP4 in Europe, without any trade-offs with other sectors, while there are trade-offs for all the other SSPs (with the environment SDI for all the remaining SSPs and additionally with the biodiversity SDI for SSP1). However, more SDIs are improved under strategy 5 in SSPs 3 and 5 compared to SSP4, even though there are trade-offs present. This indicates that for evaluating the overall efficacy of each strategy, we need to not only look at improvements and the presence/absence of trade-offs, but also the relative relationship between improvements and deteriorations in the SDIs.

The only strategy that consistently improves SDIs without any trade-offs across all regions and SSPs 3 and 4 is strategy 6 (Human and social capital). SSPs 1 and 5 have high levels of human and social capital and are thus less benefited by strategy 6. As SSPs 3 and 4 have lower capitals, they benefit from the increased coping capacity enabled by the increase in capitals in strategy 6, which results in decreased vulnerability to flooding and water over-exploitation and the projected improvement of the relevant SDIs.

Strategy 4 (Flood protection) does not have any significant effect on the indicators, as the assumed changes in scenario-specific flood risk management approaches, based on low levels of increases in the Standard of Protection of flood defences (in SSP 1, 4 and 5) and the implementation of flood resilience measures in new buildings (in SSP 3) produce only small changes in the exposed population.

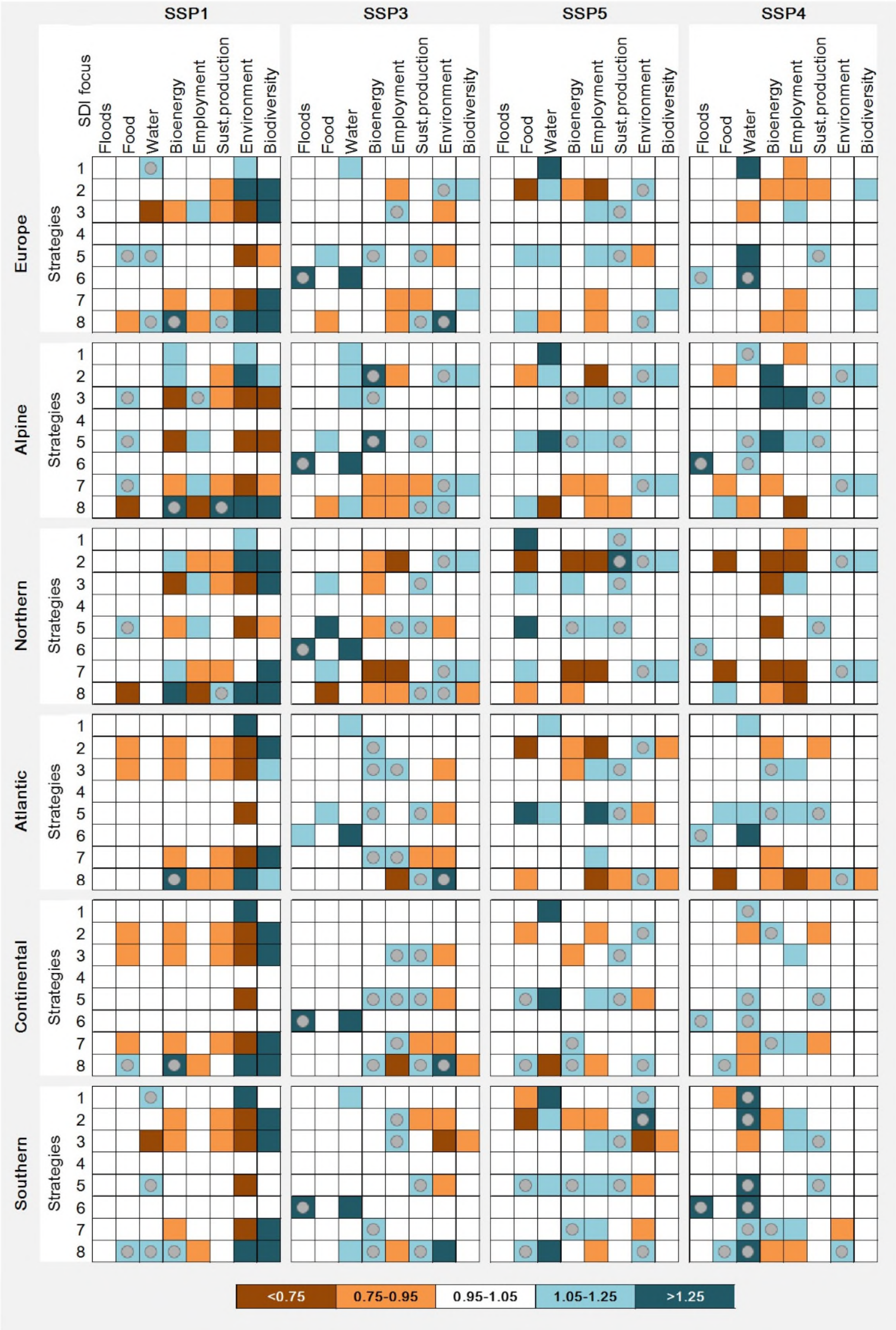

Figure 3. Effects of adaptation strategies on the SDIs, for different socio-economic scenarios (SSPs) combined with RCP2.6, for Europe and European sub-regions (StrategyX/Strategy0). Adaptation strategies correspond to: 1. Sustainable water management, 2. Maximising forest

area, 3. Land-sharing, 4. Flood protection, 5. Sustainable behaviours, 6. Human and social capital, 7. Bioenergy, 8. Agricultural intensification for land-sparing. Blue colour hues represent improvements in the SDIs (greater than 5%) and orange hues deteriorations (greater than 5%). The grey dots indicate that the improved SDI is at the same or better state as at the baseline period.

3.3. Improvements over baseline and residual climate impacts

Implementation of some adaptation strategies enables some SDIs (those marked with grey dots in Figure 3) to reach the baseline state (or an improved state). For all other SDIs, even those that improve, there are residual impacts that mean that, even when the strategies are implemented, the system is worse than its baseline state. In general, Figure 3 reveals that for most SDIs there are residual impacts -which is the difference between the SDI after the adaptation responses and the SDI in the baseline period- pushing values below baseline levels. The ability of strategies to recover the baseline state of SDIs varies considerably between regions and SSPs. For example, in the Atlantic region under SSP1, there is only one case out of the 64 combinations of SDIs x Strategies where the improvement reaches the baseline state (for the Water SDI with strategy 8). In contrast, in the Southern region under SSP4, there are 14 cases of improved SDIs out of the 64 combinations, and only three of them are shown to have residual impacts (all three associated with the employment SDI).

Moreover, improvements beyond the baseline state are more common for some SDIs than others. To better understand the behaviour of each SDI, the cases of SDI that improve (relative to strategy 0) and additionally improve over the baseline state are counted for each SDI in the Strategy x SSP scenario space. The results are included in Supplementary Tables 4 and 5 respectively. This shows that the sustainable production related SDI is the only indicator whose improvements reach or exceed the baseline state consistently for all the examined regions, whilst the flood protection, food and bioenergy related SDIs improve beyond the baseline for some regions. In all cases where the food SDI improves in the Continental and Southern regions, it improves beyond its baseline state. The improvements in the bioenergy SDI are equal to or exceed the baseline state in all cases for Europe and the sub-regions of Atlantic, Continental and Southern. Residual impacts of climate and socio-economic change that cannot be reversed after implementing adaptation strategies in all the examined regions are identified for the water, employment, environment and biodiversity indicators. Biodiversity is noticeable as the SDI most affected by residual impacts, as it never reaches the baseline state under any of the strategies and SSPs in any of the examined regions, demonstrating the inability of adaptation responses to overcome some biophysical impacts of climate change, e.g. species' climate space.

3.4. Spatial "winners" and "losers" across SSPs

The net number of improving SDIs, calculated as the difference between the number of SDIs that improve relative to strategy 0 and the number of SDIs that deteriorate, is a useful metric for examining the variations in strategy efficacy for different SSPs and regions. We calculate the percentage of net improving SDIs over the total number of SDIs across all Strategies (Figure 4a) and all SSPs (Figure 4b). The absolute numeric values used to derive the graphs in Figure 4 can be found in Supplementary Tables 6 and 7.

The net percentage of improving SDIs for each SSP and across regions (Figure 4a) indicates that the Alpine region is the relative adaptation "winner" that benefits the most from the implementation of adaptation strategies, as it is the only region with positive values of net improving SDIs across all the SSPs. Southern region has positive net percentage of improving SDIs for all but one SSP (SSP1, for which the number of SDIs that improve are equal to the number of SIs that deteriorate). The Atlantic and Continental regions are identified as "losers" under SSP1 (-11% and -9% net percentage of improving SDIs respectively), due to the negative effects of strategies 2 (Maximising forest area) and 3 (Land-sharing) on food, bioenergy, sustainability and environment related SDIs, although they have positive values for other SSPs (SSPs 3 and 4 for Atlantic, SSPs 3, 4 and 5 for Continental). Similarly, the Northern region is identified as a relative “loser” from adaptation under SSP4 (-5% net percentage of improving SDIs), due to decreased number of improving SDIs compared to the other SSPs for the same region, but has positive values for SSPs 1 and 5.

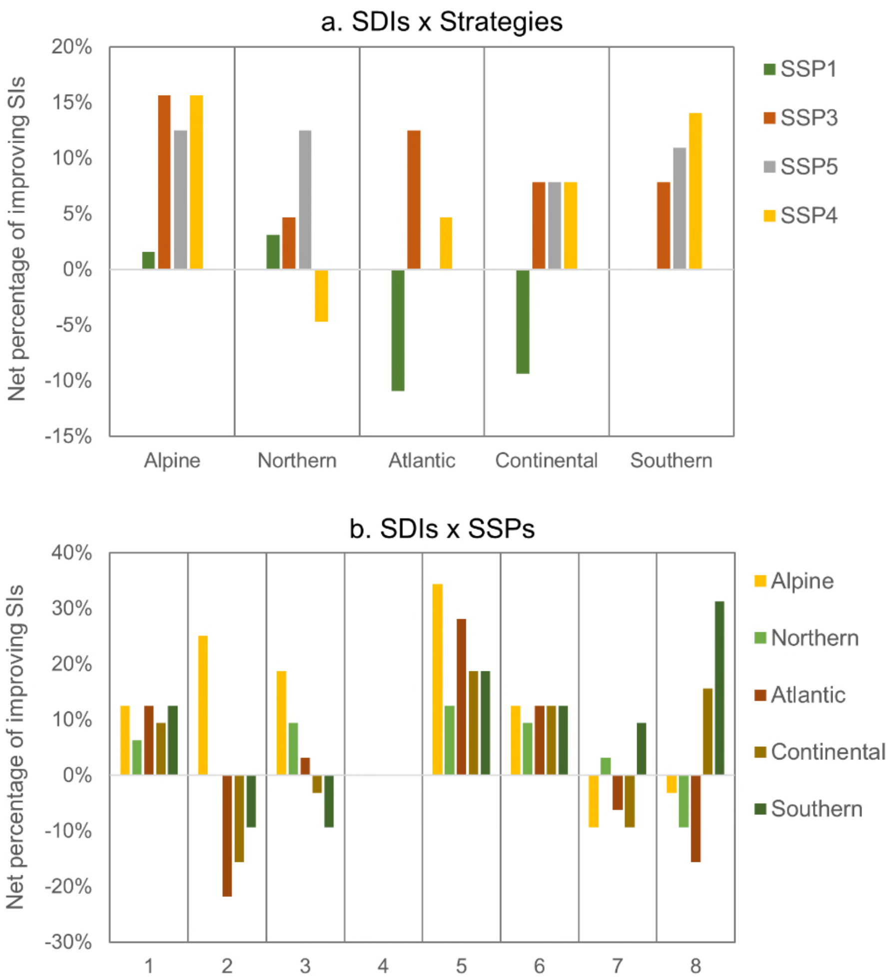

Figure 4. Net percentage of improving SDIs (aggregate number of SDIs that improve – aggregate number of SDIs that deteriorate, divided by the total number of SDIs in the scenario space, a. SDIs x Strategies scenario space (shown percentages are relative to 64 possible combinations) and b. SDIs x SSPs scenario space (shown percentages are relative to 32 possible combinations). Improvements are defined as changes greater than 1.05 and deteriorations as changes less than 0.95, as in Figures 1-2.

3.5. Adaptation strategy efficacy

The net percentage of improving SDIs for each region and across strategies (Figure 4b) indicates the strategies that are most effective for maximising synergies and minimising trade-offs between the different sectors. Strategies 1 (Sustainable water management), 5 (Sustainable behaviours) and 6 (Human and social capital) are identified as the most effective strategies, as they have positive values of net percentage of improving SDIs consistently for all the regions. Between the three strategies, the highest net percentages of improving SDIs are achieved by strategy 5 (13% to 34% across regions, compared to 6% to 13% for strategy 1 and 9% to 13% for strategy 6).

The other strategies, due to unintended impacts, cause significant trade-offs in some regions (negative values of net improving SDIs). For example, strategy 2 (Maximising forest area), is highly beneficial for the Alpine region (25%) but deteriorates more SDIs than it improves for the rest of the regions. This effect, most pronounced for the Atlantic and Continental regions (-22% and -16% respectively), is mostly due to the negative impacts of strategy 2 on the food, bioenergy, sustainability and environment related SDIs under SSP1, which relate to the competition for land when meeting food demand in the more environmentally sensitive socio-economic scenario SSP1. Strategy 7 (Bioenergy) has an overall beneficial effect for the Northern (3%) and Southern (9%) regions but negative unintended consequences for the remaining regions, mostly due to the deterioration of the bioenergy, sustainability and environment indicators in these regions. Strategy 8 (Agricultural intensification for land sparing) is highly beneficial for the Continental and Southern regions with few trade-offs between SDIs and high values of net improving SDIs of 16% and 31% respectively. However, this is not the case for the Alpine, Northern and Atlantic regions, for which the negative impacts of strategy 8 on the food, bioenergy, employment, sustainability and biodiversity SDIs exceed the overall improvements caused by the implementation of the strategy (negative net percentage of improving SIs: -3%, -9% and -16% respectively for Alpine, Northern and Atlantic).

4. Discussion

This paper presents an integrated multi-objective assessment of the scenario-specific efficacy of adaptation strategies in alleviating the combined impacts of low-end climate change and socio-economic change in Europe, as expressed by representative SDIs. The study aims to answer the urgent policy questions of what magnitude of impacts are experienced in a Paris Agreement climate in Europe, and what is the effectiveness of adaptation response options for alleviating these impacts. The present study innovates providing, to the authors' knowledge, the first Europe-focused integrated assessment of impacts of low-end climate change along with assessment of the efficacy and cross-sectoral implications of different adaptation strategies. Moreover, the present study provides a methodological innovation, by deriving and utilising sectoral indicators relevant to the social, environmental and economical components of sustainable development to express the impacts of climate change across sectors.

4.1. Environmental change impacts in a post-Paris Agreement Europe

This study has shown that there remain important impacts on society, economy and environment within a post-Paris Agreement Europe, despite the reduced level of climate change associated with the enhanced climate mitigation actions. Other studies focusing on impacts in a +1.5°C future report similar findings. Harrison et al. (2018) show that the agricultural, forestry, biodiversity, water, coastal and urban sectors in Europe are impacted by low-end climate change, even though these impacts are considerably reduced compared to high-end scenarios of climate change. Alfieri et al. (2018) found that flood risk in Europe will increase substantially, even within Paris Agreement temperature goals, as does drought risk for the Mediterranean and central Europe (Lehner et al., 2017). Various studies that look at the differences between +1.5 and +2ºC futures for freshwater availability and droughts, weather extremes indices, vulnerability to food insecurity, crop productivity, biodiversity, flooding and energy demand (Aerenson et al., 2018; Arnell et al., 2018; Betts et al., 2018; Koutroulis et al., 2018; Schleussner et al., 2018; Smith et al., 2018) agree that the negative impacts at +1.5ºC are generally less pronounced than at +2ºC and thus the Paris goal is worth pursuing, while underlining that the impacts of the lower level of warming in many cases are not negligible. Alongside the negative impacts of such low-end climate change, our study shows that there are also benefits for some sectors. However, apart from sustainable production that is consistently improving across scenarios and regions, the appearance of improvements in other indicators depends on the socio-economic scenario and varies throughout European sub-regions. Jacob et al. (2018) quantified the climate and socio-economic impacts of +1.5ºC of global warming for Europe across the energy, tourism and ecosystem sectors. They found that the negative impacts are considerable, but there are also positive impacts reported for tourism in parts of Western Europe and the energy sector over most of Europe. However, whilst the aforementioned studies assume no socio-economic changes (with the exception of Koutroulis et al. (2018) who consider alternative socio-economic pathways), this study has shown that the impacts of +1.5ºC climate change are conditioned by the future socio-economic choices made by Europe and its society.

4.2. Adaptation findings

Our study shows that adaptation actions can potentially ameliorate the impacts of climate and socio-economic change and result in an improved state of some indicators reflecting aspects of sustainable development for Europe. However, synergistic effects and improvements of such sustainability related goals will be limited by the human-environment system's capacity to fulfil their requirements. Due to the competition for finite land and water resources, regional differences in impacts and adaptation benefits within the European area are inevitable. A first determinant of the opportunities or limitations that each region will face are the impacts of climate change. Earlier studies (Dunford et al., 2015; Harrison et al., 2018) have identified the Northern region as a winner in terms of food provision under climate change, due to increased agricultural productivity resulting from the increases in temperature, whilst the Southern region has been highlighted as one of the most negatively affected regions under climate change, with projections showing decreased food production and increases in water stress. The socio-economic changes are a second determinant of regional differences which can further exacerbate or reduce the negative climate change impacts. With the regionally focused assessment of this study, we have showed how the winners and losers of climate change vary across regions and also across SSPs and sectors. In our approach, winners and losers are defined with regards to the efficacy of the adaptation strategies to improve the examined SDIs of the same time period, taking account of the constraints of the socio-economic context of the SSPs. This may cause our spatial winners and losers to differ from those of other relevant studies such as Dunford et al. (2015) and Harrison et al. (2018), where winners and losers relate to positive and negative impacts under climate and socio-economic change in comparison to the baseline period. For example, the Southern region has been identified as a negatively impacted region in the abovementioned studies but in this study it is one of the regions that most benefits from adaptation, consistently across SSPs. This arises from the increased opportunities for improvements in various sectors from implementing adaptation strategies, due to the higher negative climate change impacts for that region. Thus, this study underlines that adaptation can help alleviate environmental change impacts even in the most affected areas.

Most importantly, this study highlights that the regional and sectoral winners and losers can change dramatically due to the different socio-economic scenarios. Thus, consideration of alternative socio-economic scenarios and associated constraints in adaptation studies is of paramount importance to avoid over-optimistic outcomes and to provide a comprehensive assessment of the different adaptation options (Holman et al., 2018). Meanwhile, the societal need for adaptation to deal with climate and socio-economic change impacts combined with the complexity of responses, stress the importance for future studies to move beyond impacts/potential impacts and to further investigate residual impacts and the benefits arising from adaptation.

Many of the reported trade-offs between SDIs (mainly between the food, sustainable production, environment and biodiversity related indicators) emanate from the competition for finite land resources. The results of the present study are based on the IAP2's paradigm of aiming to meet net European food demand through varying food prices (within limits) to promote the necessary land use change to meet demand. It is inevitable that different assumptions regarding the drivers of land use change could potentially result in different synergies and trade-offs between the SDIs – for example approaches that base future land use change on changing land suitability (Brown et al., 2017) or an assumption that historical explanatory variables of land use change can be extrapolated into the future (e.g. (Fuchs et al., 2015; Verburg et al., 2009). However, such approaches can lead to societally unacceptable over- or under-supply of food (with associated consequences on e.g. food shortages) or inconsistencies with scenario logic (e.g. regarding future international trade and food import/exports; or technological innovation).

4.3. Implications for policy-making

The findings of the present study highlight the challenges for multi-objective adaptation to meet societal goals such as the SDGs. Societal goals span multiple sectors and combine environmental with social and economic considerations, making them more difficult to achieve due to feedbacks and unintended consequences from other sectors and goals. Earlier studies have stressed the importance of considering the possible unintended negative impacts of adaptation actions on other sectors (defined as "maladaptation") to optimise adaptation efficacy

(Barnett and O'Neill, 2010; Juhola et al., 2016). van Vuuren et al. (2015) show that the simultaneous achievement of SDIs relating to the food-water-energy nexus can only be realistic under purposefully comprehensive adaptation actions including systemic transformations. Understanding the inter-linkages between societal targets is crucial for taking advantage of their synergistic effects and moving towards the simultaneous achievement of these goals (Mainali et al., 2018). In our case, all but one of the adaptation strategies had unintended consequences on selected SDIs, with the exception being the strategy to increase human and social capital. This shows that trade-offs within complex socio-ecological systems (such as the trade-offs between environmental protection and employment, between food production and biodiversity or between bioenergy and the environment) are an intrinsic feature of sectoral and multi-sectoral adaptation because of competition for finite land and water resources. However, the unintended consequences differed notably between strategies, regions and socio-economic scenarios.

Moreover, our findings point to the importance of adaptation for reducing the impacts of environmental change in Europe, even in a post-Paris Agreement future. However, in terms of governance decisions and investments at the country-level, adaptation actions have not advanced as much as mitigation, while the already emerging impacts show the urgency for implementation of adaptation measures (Lesnikowski et al., 2017). Although adaptation has to be approached as a global challenge, a more precise definition of adaptation targets at the country level is necessary to avoid maladaptation during implementation of regional-scale measures (Magnan and Ribera, 2016). Finally, early adoption of adaptation strategies such as integrated water resources management (IWRM) and climate smart agriculture (CSA) can supplement and enhance mitigation targets while offsetting the adaptation cost through the achieved reduction of emissions (Dovie, 2019).

5. Conclusions

This study has presented an assessment of the efficacy of adaptation to tackle low-end climate change and socio-economic change driven impacts, expressed as indicators relating to sustainable development on Europe and its regions in the 2080s. The IMPRESSIONS Integrated Assessment Platform 2 (IAP2) was employed that represents the interactions between multiple land and water-based sectors and in which adaptation is limited by the scenario context and the scenario-specific availability of financial, human, social and manufactured capitals.

Analysis of environmental change impacts on the SDIs shows that considerable impacts are present even under low-end climate change, affecting especially biodiversity, and highlights the need for implementation of adaptation practices in a post-Paris Agreement Europe. The effectiveness of different adaptation strategies on representative SDIs show the synergies and trade-offs between SDIs and regions. Even when the SDIs improve with adaptation, residual impacts affect all the SDIs, apart from sustainable production. The most effective strategies identified by this study are those aiming at adoption of sustainable behaviours (strategy 5), implementation of sustainable water management (strategy 1) and increasing societal coping capacity through investment in increasing social and human capital (strategy 6). All of the evaluated adaptation strategies, except strategy 6, have unintended consequences on SDIs under all SSPs. The existence of such unavoidable trade-offs between the examined sectors demonstrates the importance of employing systemic approaches so as to avoid unrealistic and over-optimistic outcomes. Moreover, the socio-economic scenario dependency of the outcomes underlines the need for considering alternative socio-economic futures in adaptation studies, otherwise a considerable component of the uncertainty in projections of human-environment systems is hidden.

This assessment provides essential information for policy-makers who need to develop adaptation actions, demonstrating the complex synergies and trade-offs between adaptation strategies, sectors and European regions. Such insights on relative adaptation winners and losers builds the capacity of decision-makers to develop improved climate resilience policy and practice to reduce regional and sectoral unintended consequences whilst enhancing the opportunities afforded by the identified synergies.

This work highlights the continuing importance of adaptation even under optimistic scenarios of 1.5ºC or 2ºC of global warming. The presence of residual climate and socio-economic impacts after adaptation, even under low-end climate change, stresses the importance of early adoption of mitigation and adaptation actions and the importance of pursuing the lowest possible levels of warming.

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