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1 **Trade-offs are unavoidable in multi-objective adaptation even in a post-**

2 **Paris Agreement world**

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11 **Abstract**

12 In a post-Paris Agreement world, where global warming has been limited to 1.5 or 2ºC,

13 adaptation is still needed to address the impacts of climate change. To reinforce the links

14 between such climate actions and sustainable development, adaptation responses should be

15 aligned with goals of environmental conservation, economic development and societal

16 wellbeing. This paper uses a multi-sectoral integrated modelling platform to evaluate the

17 impacts of a +1.5ºC world to the end of the 21st century under alternative Shared

18 Socioeconomic Pathways (SSPs) for Europe. It evaluates the ability of adaptation strategies to

19 concurrently improve a range of indicators, relating to sustainable development, under the

20 constraints imposed by the contrasting SSPs. The spatial synergies and trade-offs between

21 sustainable development indicators (SDIs) are also evaluated across Europe. We find that

22 considerable impacts are present even under low-end climate change, affecting especially

23 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 1.5°C or 2°C 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 2°C 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

49   changes. Thus, the design and implementation of effective adaptation strategies should take

50   into account their long-term resilience to both climate and socio-economic changes.

51   A "roadmap" guiding the direction in which climate change adaptation responses, alongside

52   mitigation responses, need to move is provided by the principles of sustainable development

53   and multiple, diverse societal targets such as the Sustainable Development Goals (SDGs)

54   (United Nations, 2016), the Aichi Biodiversity Targets (CBD, 2010) and the Sendai Framework

55   for Disaster Risk Reduction (UNISDR, 2015). The challenging objectives set by the SDGs and

56   the Paris Agreement provide a common ground where the links between climate actions and

57   sustainable development across the social, economic and environmental pillars can be

58   positively reinforced (Gomez-Echeverri, 2018).

59   The multi-dimensionality of climate adaptation goals calls for integrated assessments that

60   consider the different components of the human - environment system and their interactions

61   (Tavoni and Levin, 2014; Verburg et al., 2016). Harrison et al. (2016) demonstrated that

62   excluding cross-sectoral interactions hinders the ability to accurately understand the

63   magnitude, direction and spatial pattern of impacts. This especially affects the water and food

64   production sectors, due to their inter-connectedness to other sectors that compete for the use of

65   the same finite land and water resources. Furthermore, Collste et al. (2017) and Mainali et al.

66   (2018) showed that integrated approaches better highlight the synergies and trade-offs between

67   different sectoral adaptation goals. Identifying the linkages between cross-sectoral goals can

68   lead to stronger synergies (Mainali et al., 2018), while utilising the identified synergies leads

69   to systemic improvements that favour the achievement of the goals (Collste et al., 2017).

70   Moreover, indicators, relating the examined sector to a measurable variable derived based on

71   scientific judgment (Pedro-Monzonís et al., 2015), are a useful tool to use in integrated

72   assessments for capturing sectoral and cross-sectoral climate impacts, which is key to providing

73   policy makers with robust findings to support decision making (von Stechow et al., 2016).

74   Adaptation responses and strategies are not immune from the socio-economic context, due to

75   the limitations of, and variability in, the capacity of different actors to adapt. This arises from

76   the influence of available economic and natural resources, social networks, entitlements,

77   institutions and governance, human resources, knowledge and technology on all levels of

78   society, from decision-makers and industries to individuals (Azhoni et al., 2017; Brooks et al.,

79   2005; Dunford et al., 2014; Moser and Ekstrom, 2010; Schneider et al., 2000). These

80   determinants of adaptive and coping capacity will be modified by the future evolution of socio-

81   economic conditions at all scales from the global (e.g. O'Neill et al., 2017), to the regional and

82   national (e.g. Kok et al., 2018; Tinch et al., 2015).

83   It is thus important that studies aiming to assess the outcomes of adaptation strategies employ

84   approaches that account for the cross-sectoral feedbacks, constraints and their differing

85   importance within alternative socio-economic futures (Rosenzweig et al., 2017; Schellnhuber

86   et al., 2014). However, very few models and studies incorporate all the above factors in their

87   framework (Holman et al., 2018). One exception is the CLIMSAVE Integrated Assessment

88   Platform or IAP (Harrison et al., 2015b), which has been used in a number of cross-sectoral

89   impact and adaptation studies (e.g. Dunford et al., 2014, 2015; Harrison et al., 2016, 2015a;

90   Holman et al., 2017; Jäger et al., 2014), and, its successor, the IMPRESSIONS IAP2 (Harrison

91   et al., 2018; Holman et al., 2017), which we utilise in this study.

92   In this paper, we use a multi-sectoral integrated modelling platform to evaluate the ability of

93   different adaptation strategies to concurrently improve a range of sustainable development-

94   related indicators, accounting for the constraints imposed by contrasting alternative socio-

95   economic futures. We focus on Europe at the end of the 21st century under the lowest

96   representative concentration pathway (RCP2.6, Moss et al., 2010; van Vuuren et al., 2007), -

97   which is broadly consistent with global warming associated with the Paris Agreement. There

98   are three main objectives for the study. Firstly, to understand the impacts of lower-end climate

99 change on a range of multi-sectoral indicators under alternative European socio-economic

100 futures. Secondly, to evaluate the efficacy of a set of adaptation strategies and the consequent

101 synergies and trade-offs between the indicators across Europe to identify sectoral 'winners'

102 and 'losers'. And thirdly, to discuss the implications of spatial variations in the trade-offs

103 between indicators from an understanding of the underlying mechanisms of the strategies, with

104 the aim of designing more effective adaptation strategies that minimise unintended

105 consequences.

2. Methods

2.1. The IMPRESSIONS Integrated Assessment Platform 2 (IAP2)

108 The IAP2 is an interactive, web-based, cross-sectoral modelling platform developed within the

109 IMPRESSIONS[1] project. IAP2 includes interlinked meta-models for a number of sectors

110 including urban development, agriculture, forestry, water provision, coastal and fluvial

111 flooding and biodiversity. It is a recent development of the widely published CLIMSAVE IAP

112 (e.g. Harrison et al., 20153a, 2016; Holman et al., 2017; Kebede et al., 2015) with the inclusion

113 of regional climate change scenarios from multiple GCM-RCMs using the Representative

114 Concentration Pathways (RCP) and European versions of the Shared Socioeconomic Pathways

115 (SSPs) as inputs to the modelling system. The evaluation of the underlying models within the

116 two versions of the platforms has been extensively published, including with sensitivity (IAP1:

117 Kebede et al., (2015); IAP2: Fronzek et al., (2019)) and uncertainty (Brown et al., 2015;

118 Dunford et al., 2015) analyses and comparative performance of stand-alone and integrated

119 model application (Harrison et al., 2016). The IAP2 results are presented at a 10' by 10'

120 (approximately 16 km × 16 km) grid-cell resolution for the European Union (including the

121 UK), Norway and Switzerland. Baseline simulations are based on 1961–1990 for climate

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

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

123 given below:

- 124 Urban expansion is simulated as a function of the scenario values of population, GDP,
125 household preference for proximity to green space versus social amenities,
126 attractiveness of the coast (scenic value versus flood risk) and strictness of the planning
127 regulations to limit sprawl. Development in urban and rural areas is given first priority
128 in the allocation of land;

- 129 Flood impacts are based on topography, relative sea-level rise or change in simulated
130 peak river flow and the estimated Standard of Protection of flood defences. The
131 probability of flood inundation constrains the suitability of floodplain land for
132 agriculture;

- 133 Water resources are simulated at a large river basin scale, with the difference between
134 simulated total water availability (driven by climate) and projected non-agricultural
135 (domestic, industrial and energy) water consumption and environmental allocation in
136 each spatial unit determining the maximum availability for agricultural irrigation;

- 137 Forest species are simulated to assess potential average annual timber yields and Net
138 Primary Production (NPP) for a range of deciduous and coniferous tree species under
139 different management regimes across Europe;

- 140 Crop yields are simulated for a range of annual and permanent crops (winter and spring
141 wheat, barley and oilseed rape, potatoes, maize, sunflower, soya, cotton, grass and
142 olives) under rainfed and irrigated conditions across Europe;

- 143 Rural land allocation for agriculture and forestry is based on constrained profit
144 maximisation (based on simulated crop and timber yields, scenario production costs
145 and prices), taking account of land availability (including constraints due to
146 urbanisation, soils and flood risk) and maximum irrigation availability, the simulated

6

147 yields of each of the crops and tree species and the demand for food and timber within

148 the scenario. The model aims to meet the demand for food and timber within Europe

149 (as a function of population, GDP, net imports, dietary preferences and bioenergy

150 demand) through iterating crop and timber prices to expand or contract agricultural and

151 managed forest areas. Land is allocated to the land use types according to relative profit

152 until demand for each commodity (cereals, oilseeds, proteins, meat, dairy, fibres and

153 timber) is met, in the order of decreasing profitability of intensive (arable) agriculture,

154 intensive (dairy) agriculture, extensive (sheep and beef) agriculture, very extensive

155 (sheep) agriculture and managed forests. Any remaining land is not used for productive

156 purposes, and is allocated to either unmanaged forest (if NPP is sufficient for

157 establishment and growth through natural succession) or unmanaged land.

158 • Species distributions are simulated for 91 species of plants, animals, birds and insects

159 that are representative of the broad range of habitats from coasts to mountains,

160 according to each species' climate suitability. The availability of both suitable climate

161 and habitat (from the rural land allocation outputs and soil types) determines potential

162 future distributions.

163 Further detailed information on the IAP2 is available in Holman et al. (2017a, 2011 for IAP2

164 and 1, respectively).

165 **2.2. Scenarios**

166 2.2.1. Climate

167 A sub-set of three climate model simulations were selected from the fifth phase of the Coupled

168 Model Intercomparison Project (CMIP5-Taylor et al., 2012), dynamically downscaled for the

169 European CORDEX domain (Jacob et al., 2014). In order to represent levels of warming

170 compatible with the Paris Agreement, the model selection was based on the availability of

171 downscaled projections following the lower-end RCP2.6 emission scenario, that project

172   warming levels of less than 1.5ºC at the end of the 21st century compared to the pre-industrial

173   period (Holman et al., 2017). GCM simulations were bias-adjusted against the CRU TS3.1

174   monthly mean data using the Delta Change method (Madsen et al., 2016). Information on the

175   selected models is summarized in Table 1.

176   The time period from 1961 to 1990 is considered as the climate baseline, while the end of 21st

177   century time-slice (2071 to 2100) is the focus of the climate projections for the present analysis.

178   This time period will be referred to as the 2080s.

179   *Table 1. Summary of the GCM-RCMs used in this study. All GCMs are based on the RCP2.6*

180   *emissions scenario. Change in average annual temperature (ΔT) and precipitation (ΔPr) is*

181   *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

182

183   2.2.2.   Socio-economics

184   The socio-economic scenarios, the "European Shared Socio-economic Pathways" (Eur-SSPs),

185   were developed as equivalent scenarios (according to the interconnectedness levels of Zurek

186   and Henrichs, 2007) to the global SSPs of O'Neil et al. (2014) as part of the IMPRESSIONS

187   project. Through an expert-driven process described in Kok et al. (2018), the global SSPs were

188   mapped onto the stakeholder-developed European scenarios of Kok et al. (2015); which were

189   extended from the 2050s to 2100 informed by the global SSPs. Trends and quantification of

190   key model parameters were then estimated for the new Eur-SSPs to facilitate their use as model

191　input (Pedde et al., 2018). Kok et al. (2018) describes the full European SSPs, but these are

192　summarised below and in Supplementary Table 1:

193　　• Eur-SSP1 (We are the World) - a strong commitment to achieve sustainable

194　　　development goals is achieved through effective governments and global cooperation,

195　　　that ultimately results in less inequality and less resource intensive lifestyles.

196　　• Eur-SSP3 (Icarus) - economic shocks in major economies and regional conflicts lead

197　　　to increased antagonism between and within regional blocks that result in the

198　　　disintegration of European social fabric and many European countries struggling to

199　　　maintain living standards.

200　　• Eur-SSP4 (Riders on the Storm) - power becomes concentrated in a political and

201　　　business elite, which is accompanied by increasing disparities in economic opportunity

202　　　that results in a substantial proportion of Europe's population having a low level of

203　　　development.

204　　• Eur-SSP5 (Fossil-fuelled Development) - increasing faith in competitive markets,

205　　　innovation and participatory societies produces rapid technological progress and

206　　　development of human capital, but is accompanied by a lack of environmental concern

207　　　and exploitation of fossil fuels.

208　Representative model input parameters used to characterise the different Eur-SSPs along with

209　their changes per Eur-SSP compared to baseline are shown in Table 2. For simplicity, the

210　developed Eur-SSPs will be referred to hereafter in the text as SSPs.

211

212   *Table 2. Selected parameters of the European socio-economics scenarios used in IAP2. The*

213   *changes in the quantitative parameters' state are for the 2080s compared to the baseline*

214   *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

215

216   **2.3. Adaptation strategies**

217   Eight different strategies to adapt to climate and socio-economic changes were considered,

218   similar to the approach of Dunford et al. (2015). Strategies aim to achieve climate resilience

219   while pursuing a range of goals relating to sustainable development, by specifically targeting

220   and investing in water, forestry, environment, flood protection, behavioural changes, society,

221   bioenergy and food production. The adaptation strategies were applied within the SSPs through

222   changing the socio-economic inputs to the IAP2.

223   The differing capacity to adapt between the SSPs are reflected in scenario-specific adaptation

224   limits to the numerical model inputs in the IAP2. These limits are prescribed as a function of:

225   • the unconstrained range of input values that are plausible and consistent with the

226   underlying socio-economic scenario storyline;

227   • the consistency between the broad type of adaptation (human, technological, financial

228   etc.) and the scenario narrative, i.e. behavioural adaptation would be expected to be

229   more effective in an SSP such as SSP1 characterised by high human and social capital;

230   and

231   •   the availability of the most limiting capital (human, social, manufactured or financial)

232   within the SSP for the given adaptation.

233   Each adaptation strategy was implemented by changing the model inputs to the adaptation limit

234   (maximum or minimum) within the above scenario constraints.

235   To assess the efficacy of the strategies, a "No action" strategy is also considered (Strategy0)

236   which expresses the impacts of the combined climate and socio-economic changes without any

237   planned adaptation actions. A description of the adaptation strategies, and the model settings

238   used to implement them in IAP2, are shown in Table 3.

239

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↑

242

2.4. Sustainable development indicators

244 To assess the impacts of the climate and socio-economic scenarios and the efficacy of

245 adaptation strategies, we used indicators relating to different aspects of sustainable

246 development. These sustainable development indicators (hereafter, SDIs) were derived from

247 different social, environmental and economic components of the IAP2 outputs to depict human-

248 environment system interactions. Eight indicators within the three pillar framework of

249 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 |

256

257 The SDIs were evaluated for Europe and for five biogeographical European sub-regions

258 (Alpine, Northern, Atlantic, Continental and Southern, shown in Figure 1) defined by Metzger

259 et al. (2005), to examine spatial differences in adaptation effectiveness and trade-offs.

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261
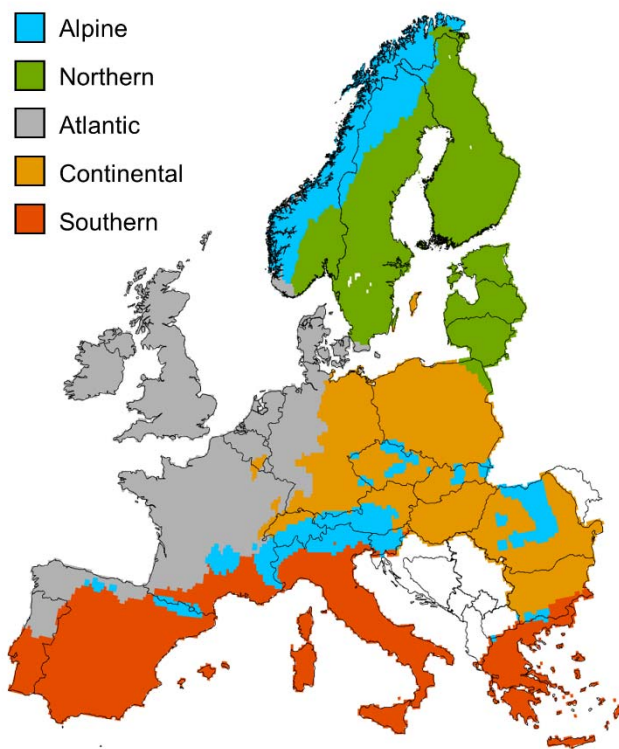
Figure 1. The IAP2 domain, split into European sub-regions, defined by Metzger et al., (2005).

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.

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275   Based on this framework, three types of effects are examined here. First, the effects of climate

276   and socio-economic changes on an SDI compared to baseline conditions, under no action

277   (Strategy0$_{SSPn}$/Baseline). Second, the efficacy of a strategy compared to no action, under

278   climate and socio-economic changes (StrategyX $_{SSPn}$ /Strategy0 $_{SSPn}$). And finally, the efficacy

279   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

282   The impacts of the climate and socio-economic scenarios on the examined SDIs in the 2080s

283   compared to the baseline period are depicted in Figure 2. For the analysis we considered the

284   ensemble mean of the results produced by the three climate models. Single model results are

285   not presented as the variation in their projections of land use classes is small (Supplementary

286   Table 2). Moreover, due to the spatial aggregation for the calculation of changes in SDIs, results

287   from the different ensemble members fall into the same category of change (Supplementary

288   Figure 1).

289   Low-end climate change (RCP2.6) and varying socio-economic changes are associated with

290   both positive and negative effects on the examined SDIs, and these differ notably for the

291   different SSPs (Figure 2). For example, the majority of the indicators (five out of eight)

292   improve under SSP1 (flood protection, food, water, bioenergy and sustainable production),

293   while only three out of eight show improvements under SSP5 (bioenergy, sustainable

294   production and environment) when aggregated at the European scale. SSP3 and SSP4 both

295   show improvements for four out of the eight indicators; food, water and biodiversity improve

296   for both SSPs, whilst flood protection also improves in SSP3 and employment in SSP4. The

297   SSP dependency of the impacts is also observed across the European sub-regions. For example,

298   flood protection, food and water related SDIs improve for most sub-regions under SSP1 (four

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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
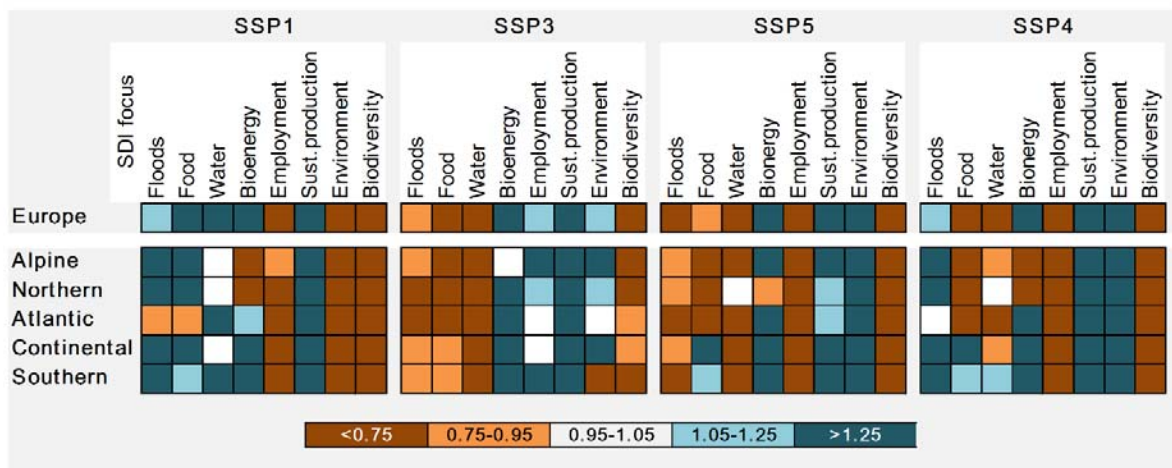
scenario SSP1.

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

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317   environment SDI (which corresponds to total forest area) in SSP1, but increases for the other

318   SSPs that result in increased forest coverage compared to the baseline period. Forest area

319   reduction in SSP1 is caused by expansion of the agricultural (arable and grassland) land use

320   classes, as a response of the model to the environmentally-friendly lower intensity agricultural

321   production systems within SSP1 and the decreased food imports (to reduce environmental

322   footprint) in the scenario, signifying that a greater component of the European food demand

323   has to be covered by food grown within Europe. The expansion of agricultural areas in SSP1

324   in order to meet net food demand explains the improvement of the food SDI shown in Figure

325   2. Alternatively, the food SDI deteriorates under SSP3, a scenario of decreases in net food

326   imports (although smaller compared to SSP1), decreased wealth (as expressed by Gross

327   Domestic Product) and a decreased European population. In the case of SSP3, the overall

328   decreased demand for food can be met with a small agricultural production area, so a larger

329   proportion of the population are potentially vulnerable to food insecurity due to a reliance on

330   less effective food distribution systems in this fragmented Europe.

331   **3.2. Effect of adaptation strategy implementation**

332   The effects of implementing each of the eight adaptation strategies within the context of the

333   four SSPs combined with RCP2.6 on the SDIs for Europe and the five sub-regions are

334   graphically summarised in Figure 3. The numeric values corresponding to the colour hues in

335   Figure 3 are tabulated in Supplementary Table 3 of the ESM. The grey dots in the improving

336   SDIs indicate that, after the strategy implementation, the SDI state is the same or better than at

337   the baseline period.

338   Figure 3 reveals the complex cross-sectoral interactions associated with the different adaptation

339   strategies, which results in various synergies and trade-offs across SDIs and regions. There is

340   no single strategy that improves all the SDIs and unintended trade-offs are present in all the

341   strategies for at least one SSP. For example, for Europe, strategy 1 (Sustainable water

342 management) has positive effects for the water related SDI for all SSPs, for the environment

343 SDI for SSP1, but negative impacts on employment for SSP4. For SSP1, the improved

344 environment SDI can be attributed to increased agricultural productivity due to more effective

345 water management and irrigation, which allows land use transitions to increase forest areas.

346 For other SSPs this transition does not considerably affect the environment SDI as they already

347 have higher forest coverage. In contrast, the reduction of agriculturally productive areas leads

348 to the deterioration of the employment SDI in SSP4. Another representative example of the

349 SSP dependency of the efficacy and trade-offs associated with the adaptation strategies is

350 strategy 8 (Agricultural intensification for land-sparing) for Europe. In this case, the water,

351 bioenergy and biodiversity SDIs only improve for SSP1 while they exhibit no change for the

352 other SSPs (or even deteriorate in the case of the water SDI in SSP5 and the bioenergy SDI in

353 SSP4). This is because SSP1 has such a shortage of land other than agriculture that land sparing

354 makes a real difference by freeing up land for other land uses, such as forests (improved

355 environment SDI) and habitats for different species (improved biodiversity SDI). The same

356 logic explains the deterioration of the employment SDI under all the SSPs with strategy 8 (as

357 agricultural areas have a higher relative employment requirement than managed forest).

358 Strategy 5 (Sustainable behaviours) improves two SDIs (water and sustainability) for SSP4 in

359 Europe, without any trade-offs with other sectors, while there are trade-offs for all the other

360 SSPs (with the environment SDI for all the remaining SSPs and additionally with the

361 biodiversity SDI for SSP1). However, more SDIs are improved under strategy 5 in SSPs 3 and

362 5 compared to SSP4, even though there are trade-offs present. This indicates that for evaluating

363 the overall efficacy of each strategy, we need to not only look at improvements and the

364 presence/absence of trade-offs, but also the relative relationship between improvements and

365 deteriorations in the SDIs.

366   The only strategy that consistently improves SDIs without any trade-offs across all regions and

367   SSPs 3 and 4 is strategy 6 (Human and social capital). SSPs 1 and 5 have high levels of human

368   and social capital and are thus less benefited by strategy 6. As SSPs 3 and 4 have lower capitals,

369   they benefit from the increased coping capacity enabled by the increase in capitals in strategy

370   6, which results in decreased vulnerability to flooding and water over-exploitation and the

371   projected improvement of the relevant SDIs.

372   Strategy 4 (Flood protection) does not have any significant effect on the indicators, as the

373   assumed changes in scenario-specific flood risk management approaches, based on low levels

374   of increases in the Standard of Protection of flood defences (in SSP 1, 4 and 5) and the

375   implementation of flood resilience measures in new buildings (in SSP 3) produce only small

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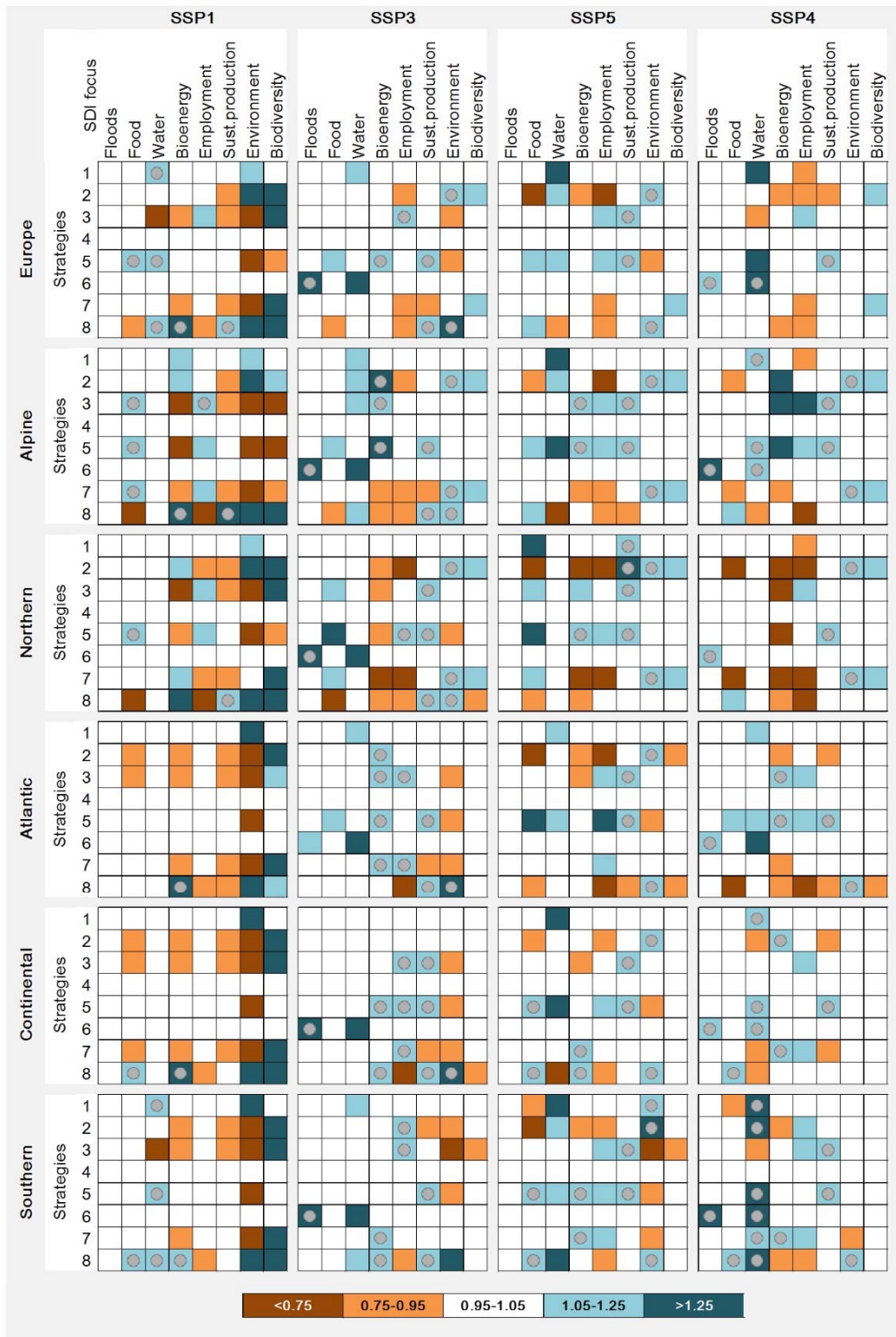
Figure 3. Effects of adaptation strategies on the SDIs, for different socio-economic scenarios
(SSPs) combined with RCP2.6, for Europe and European sub-regions (StrategyX/Strategy0).
Adaptation strategies correspond to: 1. Sustainable water management, 2. Maximising forest

381 *area, 3. Land-sharing, 4. Flood protection, 5. Sustainable behaviours, 6. Human and social*

382 *capital, 7. Bioenergy, 8. Agricultural intensification for land-sparing. Blue colour hues*

383 *represent improvements in the SDIs (greater than 5%) and orange hues deteriorations (greater*

384 *than 5%). The grey dots indicate that the improved SDI is at the same or better state as at the*

385 *baseline period.*

386 **3.3. Improvements over baseline and residual climate impacts**

387 Implementation of some adaptation strategies enables some SDIs (those marked with grey dots

388 in Figure 3) to reach the baseline state (or an improved state). For all other SDIs, even those

389 that improve, there are residual impacts that mean that, even when the strategies are

390 implemented, the system is worse than its baseline state. In general, Figure 3 reveals that for

391 most SDIs there are residual impacts -which is the difference between the SDI after the

392 adaptation responses and the SDI in the baseline period- pushing values below baseline levels.

393 The ability of strategies to recover the baseline state of SDIs varies considerably between

394 regions and SSPs. For example, in the Atlantic region under SSP1, there is only one case out

395 of the 64 combinations of SDIs x Strategies where the improvement reaches the baseline state

396 (for the Water SDI with strategy 8). In contrast, in the Southern region under SSP4, there are

397 14 cases of improved SDIs out of the 64 combinations, and only three of them are shown to

398 have residual impacts (all three associated with the employment SDI).

399 Moreover, improvements beyond the baseline state are more common for some SDIs than

400 others. To better understand the behaviour of each SDI, the cases of SDI that improve (relative

401 to strategy 0) and additionally improve over the baseline state are counted for each SDI in the

402 Strategy x SSP scenario space. The results are included in Supplementary Tables 4 and 5

403 respectively. This shows that the sustainable production related SDI is the only indicator whose

404 improvements reach or exceed the baseline state consistently for all the examined regions,

405 whilst the flood protection, food and bioenergy related SDIs improve beyond the baseline for

25

406 some regions. In all cases where the food SDI improves in the Continental and Southern

407 regions, it improves beyond its baseline state. The improvements in the bioenergy SDI are

408 equal to or exceed the baseline state in all cases for Europe and the sub-regions of Atlantic,

409 Continental and Southern. Residual impacts of climate and socio-economic change that cannot

410 be reversed after implementing adaptation strategies in all the examined regions are identified

411 for the water, employment, environment and biodiversity indicators. Biodiversity is noticeable

412 as the SDI most affected by residual impacts, as it never reaches the baseline state under any

413 of the strategies and SSPs in any of the examined regions, demonstrating the inability of

414 adaptation responses to overcome some biophysical impacts of climate change, e.g. species'

415 climate space.

416 **3.4. Spatial "winners" and "losers" across SSPs**

417 The net number of improving SDIs, calculated as the difference between the number of SDIs

418 that improve relative to strategy 0 and the number of SDIs that deteriorate, is a useful metric

419 for examining the variations in strategy efficacy for different SSPs and regions. We calculate

420 the percentage of net improving SDIs over the total number of SDIs across all Strategies

421 (Figure 4a) and all SSPs (Figure 4b). The absolute numeric values used to derive the graphs in

422 Figure 4 can be found in Supplementary Tables 6 and 7.

423 The net percentage of improving SDIs for each SSP and across regions (Figure 4a) indicates

424 that the Alpine region is the relative adaptation "winner" that benefits the most from the

425 implementation of adaptation strategies, as it is the only region with positive values of net

426 improving SDIs across all the SSPs. Southern region has positive net percentage of improving

427 SDIs for all but one SSP (SSP1, for which the number of SDIs that improve are equal to the

428 number of SIs that deteriorate). The Atlantic and Continental regions are identified as "losers"

429 under SSP1 (-11% and -9% net percentage of improving SDIs respectively), due to the negative

430 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.
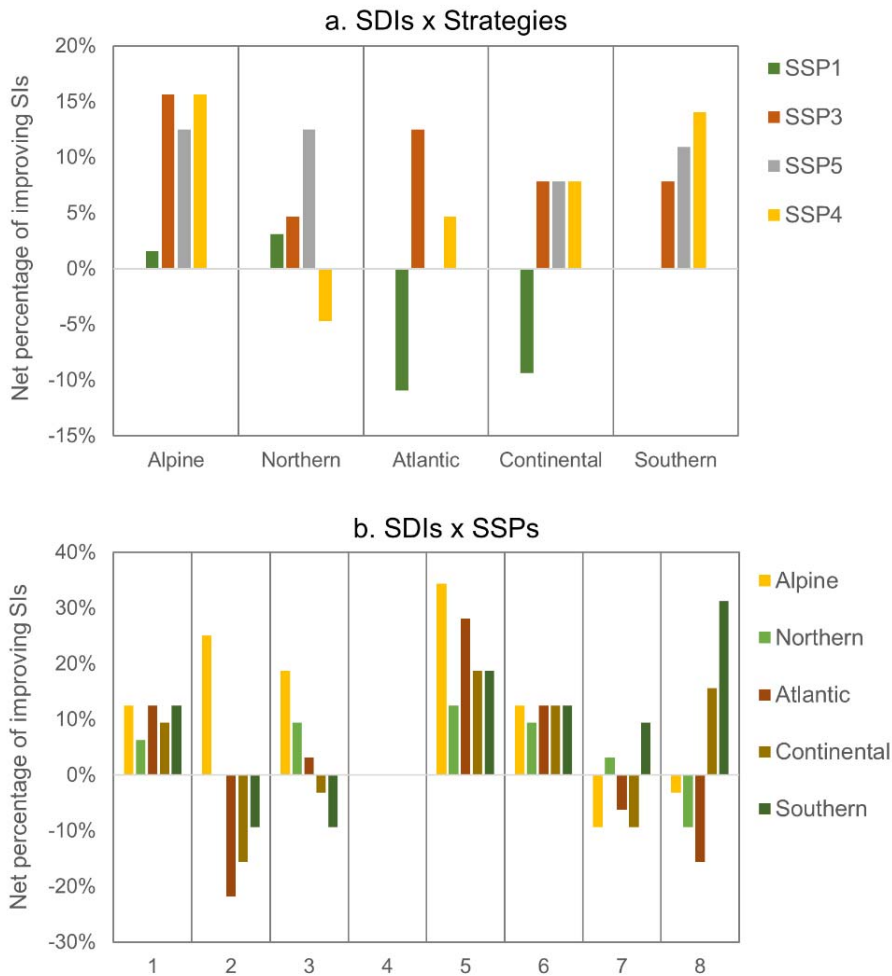
Figure 4. Net percentage of improving SDIs (aggregate number of SDIs that improve – aggregate number of SDIs that deteriorate, divided by the total number of SDIs in the scenario space, a. SDIs x Strategies scenario space (shown percentages are relative to 64 possible combinations) and b. SDIs x SSPs 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

28

468 percentage of improving SIs: -3%, -9% and -16% respectively for Alpine, Northern and
469 Atlantic).

4. Discussion

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

482   4.1.Environmental change impacts in a post-Paris Agreement Europe

483 This study has shown that there remain important impacts on society, economy and
484 environment within a post-Paris Agreement Europe, despite the reduced level of climate
485 change associated with the enhanced climate mitigation actions. Other studies focusing on
486 impacts in a +1.5ºC future report similar findings. Harrison et al. (2018) show that the
487 agricultural, forestry, biodiversity, water, coastal and urban sectors in Europe are impacted by
488 low-end climate change, even though these impacts are considerably reduced compared to
489 high-end scenarios of climate change. Alfieri et al. (2018) found that flood risk in Europe will
490 increase substantially, even within Paris Agreement temperature goals, as does drought risk for
491 the Mediterranean and central Europe (Lehner et al., 2017). Various studies that look at the

492   differences between +1.5 and +2ºC futures for freshwater availability and droughts, weather

493   extremes indices, vulnerability to food insecurity, crop productivity, biodiversity, flooding and

494   energy demand (Aerenson et al., 2018; Arnell et al., 2018; Betts et al., 2018; Koutroulis et al.,

495   2018; Schleussner et al., 2018; Smith et al., 2018) agree that the negative impacts at +1.5ºC are

496   generally less pronounced than at +2ºC and thus the Paris goal is worth pursuing, while

497   underlining that the impacts of the lower level of warming in many cases are not negligible.

498   Alongside the negative impacts of such low-end climate change, our study shows that there are

499   also benefits for some sectors. However, apart from sustainable production that is consistently

500   improving across scenarios and regions, the appearance of improvements in other indicators

501   depends on the socio-economic scenario and varies throughout European sub-regions. Jacob et

502   al. (2018) quantified the climate and socio-economic impacts of +1.5ºC of global warming for

503   Europe across the energy, tourism and ecosystem sectors. They found that the negative impacts

504   are considerable, but there are also positive impacts reported for tourism in parts of Western

505   Europe and the energy sector over most of Europe. However, whilst the aforementioned studies

506   assume no socio-economic changes (with the exception of Koutroulis et al. (2018) who

507   consider alternative socio-economic pathways), this study has shown that the impacts of +1.5ºC

508   climate change are conditioned by the future socio-economic choices made by Europe and its

509   society.

510   4.2. Adaptation findings

511   Our study shows that adaptation actions can potentially ameliorate the impacts of climate and

512   socio-economic change and result in an improved state of some indicators reflecting aspects of

513   sustainable development for Europe. However, synergistic effects and improvements of such

514   sustainability related goals will be limited by the human-environment system's capacity to

515   fulfil their requirements. Due to the competition for finite land and water resources, regional

516   differences in impacts and adaptation benefits within the European area are inevitable. A first

517   determinant of the opportunities or limitations that each region will face are the impacts of

518   climate change. Earlier studies (Dunford et al., 2015; Harrison et al., 2018) have identified the

519   Northern region as a winner in terms of food provision under climate change, due to increased

520   agricultural productivity resulting from the increases in temperature, whilst the Southern region

521   has been highlighted as one of the most negatively affected regions under climate change, with

522   projections showing decreased food production and increases in water stress. The socio-

523   economic changes are a second determinant of regional differences which can further

524   exacerbate or reduce the negative climate change impacts. With the regionally focused

525   assessment of this study, we have showed how the winners and losers of climate change vary

526   across regions and also across SSPs and sectors. In our approach, winners and losers are defined

527   with regards to the efficacy of the adaptation strategies to improve the examined SDIs of the

528   same time period, taking account of the constraints of the socio-economic context of the SSPs.

529   This may cause our spatial winners and losers to differ from those of other relevant studies

530   such as Dunford et al. (2015) and Harrison et al. (2018), where winners and losers relate to

531   positive and negative impacts under climate and socio-economic change in comparison to the

532   baseline period. For example, the Southern region has been identified as a negatively impacted

533   region in the abovementioned studies but in this study it is one of the regions that most benefits

534   from adaptation, consistently across SSPs. This arises from the increased opportunities for

535   improvements in various sectors from implementing adaptation strategies, due to the higher

536   negative climate change impacts for that region. Thus, this study underlines that adaptation can

537   help alleviate environmental change impacts even in the most affected areas.

538   Most importantly, this study highlights that the regional and sectoral winners and losers can

539   change dramatically due to the different socio-economic scenarios. Thus, consideration of

540   alternative socio-economic scenarios and associated constraints in adaptation studies is of

541   paramount importance to avoid over-optimistic outcomes and to provide a comprehensive

542   assessment of the different adaptation options (Holman et al., 2018). Meanwhile, the societal

543   need for adaptation to deal with climate and socio-economic change impacts combined with

544   the complexity of responses, stress the importance for future studies to move beyond

545   impacts/potential impacts and to further investigate residual impacts and the benefits arising

546   from adaptation.

547   Many of the reported trade-offs between SDIs (mainly between the food, sustainable

548   production, environment and biodiversity related indicators) emanate from the competition for

549   finite land resources. The results of the present study are based on the IAP2's paradigm of

550   aiming to meet net European food demand through varying food prices (within limits) to

551   promote the necessary land use change to meet demand. It is inevitable that different

552   assumptions regarding the drivers of land use change could potentially result in different

553   synergies and trade-offs between the SDIs – for example approaches that base future land use

554   change on changing land suitability (Brown et al., 2017) or an assumption that historical

555   explanatory variables of land use change can be extrapolated into the future (e.g. (Fuchs et al.,

556   2015; Verburg et al., 2009). However, such approaches can lead to societally unacceptable

557   over- or under-supply of food (with associated consequences on e.g. food shortages) or

558   inconsistencies with scenario logic (e.g. regarding future international trade and food

559   import/exports; or technological innovation).

560   4.3.Implications for policy-making

561   The findings of the present study highlight the challenges for multi-objective adaptation to

562   meet societal goals such as the SDGs. Societal goals span multiple sectors and combine

563   environmental with social and economic considerations, making them more difficult to achieve

564   due to feedbacks and unintended consequences from other sectors and goals. Earlier studies

565   have stressed the importance of considering the possible unintended negative impacts of

566   adaptation actions on other sectors (defined as "maladaptation") to optimise adaptation efficacy

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567 (Barnett and O'Neill, 2010; Juhola et al., 2016). van Vuuren et al. (2015) show that the

568 simultaneous achievement of SDIs relating to the food-water-energy nexus can only be realistic

569 under purposefully comprehensive adaptation actions including systemic transformations.

570 Understanding the inter-linkages between societal targets is crucial for taking advantage of

571 their synergistic effects and moving towards the simultaneous achievement of these goals

572 (Mainali et al., 2018). In our case, all but one of the adaptation strategies had unintended

573 consequences on selected SDIs, with the exception being the strategy to increase human and

574 social capital. This shows that trade-offs within complex socio-ecological systems (such as the

575 trade-offs between environmental protection and employment, between food production and

576 biodiversity or between bioenergy and the environment) are an intrinsic feature of sectoral and

577 multi-sectoral adaptation because of competition for finite land and water resources. However,

578 the unintended consequences differed notably between strategies, regions and socio-economic

579 scenarios.

580 Moreover, our findings point to the importance of adaptation for reducing the impacts of

581 environmental change in Europe, even in a post-Paris Agreement future. However, in terms of

582 governance decisions and investments at the country-level, adaptation actions have not

583 advanced as much as mitigation, while the already emerging impacts show the urgency for

584 implementation of adaptation measures (Lesnikowski et al., 2017). Although adaptation has to

585 be approached as a global challenge, a more precise definition of adaptation targets at the

586 country level is necessary to avoid maladaptation during implementation of regional-scale

587 measures (Magnan and Ribera, 2016). Finally, early adoption of adaptation strategies such as

588 integrated water resources management (IWRM) and climate smart agriculture (CSA) can

589 supplement and enhance mitigation targets while offsetting the adaptation cost through the

590 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.

615 This assessment provides essential information for policy-makers who need to develop

616 adaptation actions, demonstrating the complex synergies and trade-offs between adaptation

617 strategies, sectors and European regions. Such insights on relative adaptation winners and

618 losers builds the capacity of decision-makers to develop improved climate resilience policy

619 and practice to reduce regional and sectoral unintended consequences whilst enhancing the

620 opportunities afforded by the identified synergies.

621 This work highlights the continuing importance of adaptation even under optimistic scenarios

622 of 1.5°C or 2°C of global warming. The presence of residual climate and socio-economic

623 impacts after adaptation, even under low-end climate change, stresses the importance of early

624 adoption of mitigation and adaptation actions and the importance of pursuing the lowest

625 possible levels of warming.

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