The CLIMSAVE Project

Climate Change Integrated Assessment Methodology for Cross-Sectoral Adaptation and Vulnerability in Europe

Report on identification of key impacts and metrics for cross-sectoral comparison

A.S. Kebede[1], R. Dunford[2], P.A. Harrison[2], I.P. Holman[3], E. Audsley[3], M. Mokrech[1], R.J. Nicholls[1], S. Rickebusch[4], M.D.A. Rounsevell[4], S. Sabaté[5], F. Sallaba[6], A. Sanchez[5], C.-M. Savin[7], M. Trnka[8], F. Wimmer[9] and B. Stuch[9]

[1] *Faculty of Engineering and the Environmental, University of Southampton, UK*
[2] *Environmental Change Institute, University of Oxford, UK*
[3] *Environmental Science and Technology Department, Cranfield University, UK*
[4] *Centre for the study of Environmental Change and Sustainability, University of Edinburgh, UK*
[5] *CREAF, Autonomous University of Barcelona, Spain*
[6] *Department of Earth and Ecosystem Services, University of Lund, Sweden*
[7] *TIAMASG Foundation, Romania*
[8] *Institute of Agrosystems and Bioclimatology, Mendel University in Brno, Czech Republic*
[9] *Center for Environmental Systems Research, University of Kassel, Germany*

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Table of contents

0. Preface ... 3
1. Introduction ... 3
2. Methods ... 5
    2.1 The CLIMSAVE IA Platform ... 5
    2.2 Climate and socio-economic scenarios ... 5
    2.3 Regions ... 6
    2.4 Indicators ... 7
3. Sensitivity analysis ... 7
    3.1 Sensitivity methodology ... 7
    3.2 Sensitivity results ... 10
4. Scenario analysis ... 13
    4.1 Scenario methodology ... 13
    4.2 Scenario results ... 14
5. Discussion ... 22
    5.1 Cross-sectoral impacts: which sectors are winners and losers? ... 22
    5.2 Methodological limitations ... 22
    5.3 Vulnerability and human well-being ... 23
    5.4 Scenario uncertainty and the adaptation screen ... 23
6. Conclusions ... 24
7. References ... 24

Appendices

A. Additional graphs for the scenario analysis ... 28

0. Preface

The purpose of this deliverable is to analyse the outputs from the CLIMSAVE Integrated Assessment (IA) Platform to identify those sectors (and their components) which are most exposed and sensitive to climate change, including important cross-sectoral linkages. This is achieved by a combined approach drawing on sensitivity analysis and scenario analysis. In the *sensitivity analysis* the full range of input variables for the IA Platform are explored whilst the *scenario analysis* focuses on the climate and socio-economic scenarios selected within the project (see Deliverables 3.4 and 1.1 respectively).

1. Introduction

Climate is changing and there is considerable scientific evidence that shows that it is linked to human-induced emissions of greenhouse gases (IPCC, 2007). The changes in climate are expected to intensify through the 21st century (Meehl et al., 2007), and are likely to have profound impacts on the social, economic and environmental sustainability and well-being of human societies and natural systems worldwide (IPCC, 2007). Hence, the problem of climate change remains one of the most important environmental and scientific challenges that will be faced in the coming decades. Managing this global environmental challenge is complicated by the problem of an "unknowable future". The future of the climate system is uncertain and dynamic in itself: however, the direction of travel of many key environmental parameters will also be driven by socio-economics and reflect decisions based on social, ethical, political and institutional factors that are even harder to predict and model.

Impacts on human well-being and the health of natural systems include: (1) a decline in agricultural productivity that threatens food security (e.g. Audsley et al., 2006; Aydinalp and Cresser, 2008; Iglesias et al., 2009; Nelson et al., 2009); (2) shifts in species distribution and the composition of habitats and ecosystems that characterise landscapes (e.g. Berry et al., 2006; Green et al., 2003); (3) an altered risk of flooding for people and properties plus their associated damages and costs (e.g. Brown et al., 2001; Costa et al., 2009; Feyen et al, 2006; Richards and Nicholls, 2009); (4) changed wild fire risk and adverse effects of prolonged drought on forest growth and wood production (e.g. Ciais et al., 2005; Lindner et al., 2008); and (5) altered hydrological processes and regimes, and their effects on the availability, quality and use of water resources (e.g. Bates et al., 2008; EEA, 2007). The extent and magnitudes of these potential impacts vary: (i) over time; (ii) across regions, ecosystems and sectors; and (iii) with the ability of these regions, ecosystems and sectors to adapt, mitigate and cope with these changes. Nevertheless, such consequences pose significant threats to all sectors of society and the environment at all scales, ranging from local to global spatial, and short- to long-term temporal, scales (IPCC, 2007).

Furthermore, impacts occurring in one sector are not likely to be confined to that sector: this leads to the potential for cascading indirect effects with far reaching repercussions across different sectors (e.g. Nicholls and Kebede, 2012; World Bank, 2013). Cross-sectoral interactions are important since changes in one sector can affect another sector either directly, e.g. changes in land use affect regional hydrology or biodiversity, or indirectly through policy, e.g. measures designed for coastal flood defence also impact on coastal habitat (Holman et al. 2008a,b). However, most impact studies treat each sector independently thereby ignoring important feedbacks and cross-sectoral interactions. Ignoring cross-sectoral interactions can lead to either over- or under-estimation of climate change impacts and the need for adaptation (Carter et al. 2007). Yet in spite of this only a few climate impacts studies adopt a cross-sectoral approach.

At the global scale, Integrated Assessment Models (IAMs) (e.g. van Vuuren et al. 2011), often combined with computable general equilibrium (CGE) models (e.g. Hertel et al. 2011), are used to project impacts across of range of sectors in climate change assessments. IAMs and CGE models have acknowledged strengths in providing comprehensive cross-sectoral analyses, but have been criticised for the simplistic way in which they represent some processes and a lack of spatial differentiation (Rounsevell et al. 2013). CGE models, for example, are based on sectors rather than geographic space and are rarely resolved below the level of world regions or countries. Busch (2006) demonstrated the large divergence between IAMs and regional scale models in scenario studies of land use change in Europe. Even the direction of change was found to be considerably different with, for example, IAMs projecting increases in cropland areas, but regional scale models projecting decreases (Busch 2006).

However, understanding global environmental changes requires understanding intrinsically regional phenomena within an integrated framework (Hibbard and Janetos, 2013). Although there are numerous regional integrated assessment studies published, there are relatively few that link impact models (e.g. Rounsevell et al. 2006 - agriculture and biodiversity; Kirchen et al. 2008 - multiple urban infrastructure types; Xiong et al. 2010; Barthel et al. 2012 - water and agriculture; Baruffi et al. 2012 - surface and groundwater resources) and fewer still that both integrate between multiple sectors <u>and</u> consider climate and socio-economic change (e.g. Holman et al. 2005; Holman et al. 2008a; Harrison et al. 2013).

Climate change impacts will interact with those associated with continuing socio-economic and political changes, in potentially complex, non-additive ways. Yet, many previous climate change impact assessment studies have tended to focus on climate drivers only. Other environmental change drivers, such as socio-economic and political changes, have been given considerably less attention and, when considered, are often treated independently rather than holistically (Holman et al., 2006).

Since the future is unknown, scenario analysis is often used in climate change assessments to account for alternative, future socio-economic development pathways and their implications for climate change (Rounsevell and Metzger 2010). Scenarios encapsulate the uncertainties associated with social and political changes that are impossible to foresee through a series of ‘what if?’ experiments that explore plausible, i.e. not impossible, future states of the world or a region. However, the scenario approach can itself introduce other uncertainties deriving from the limits to knowledge, personal judgement (including beliefs and axiomatic preconceptions), and the quantification of scenarios with models (Rounsevell and Metzger, 2010). However, whilst such limitations are known, scenarios still offer a tractable and enriching approach to explore alternative futures, especially when applied within a stakeholder, participatory context. The development of scenarios with stakeholders enables the exploitation of a wide range of tacit knowledge and experience, especially at the regional scale (e.g. Deliverable 3.3).

This deliverable applies sensitivity and scenario analysis to the CLIMSAVE IA Platform in an effort to better understand the cross-sectoral impacts of a range of potential futures. The effects of independent changes in a wide range of climate and socio-economic drivers on the six sectors considered in CLIMSAVE (agriculture, forests, biodiversity, water, coasts and urban) is first assessed using sensitivity analysis. The IA Platform was then applied to a wide range of climate and socio-economic scenarios to investigate both direct and indirect impacts resulting from different scenario uncertainties.

2. Methods

2.1 The CLIMSAVE IA Platform

The CLIMSAVE IA Platform is an interactive, exploratory, web-based tool for assessing climate change impacts and vulnerabilities on a range of sectors, including agriculture, forests, biodiversity, coasts, water resources, and urban development (Deliverable 2.4; Harrison et al. 2013). The Platform integrates a suite of sectoral models to spatially simulate the impacts of different climate and socio-economic scenarios on these sectors across Europe, allowing the evaluation of cross-sectoral benefits, conflicts and trade-offs. In order to enable greater complexity of model linkages to be represented within the IA Platform and facilitate a relatively fast run time, a meta-modelling approach was used whereby computationally efficient or reduced-form models that emulate the performance of more complex models were developed (Harrison et al. 2013). The Platform operates at a spatial resolution of 10 arcmin x 10 arcmin (approximately 16km x 16km in Europe) and produces outputs on both sector-based impact indicators and ecosystem services in order to link climate change impacts directly to human well-being.

Both sensitivity and scenario analyses draw on the outputs from a "batch mode" version of the IA Platform designed to process a large number of runs offline. The runs needed for each approach are different and are detailed in Sections 3.1 and 4.1.

2.2 Climate and socio-economic scenarios

The CLIMSAVE IA Platform incorporates a range of climate and socio-economic scenarios which can be selected either independently or in combination for two timeslices (either the 2020s or 2050s). The user can then explore how impacts and cross-sectoral interactions change for different scenario combinations.

2.2.1 Climate scenarios

For the climate change scenarios, the user can select the IPCC emissions scenario (A1b, A2, B1 or B2), the global climate model (GCM) and the climate sensitivity (low, medium or high). Five GCMs are included within the IA Platform representing the "best" available GCM (MPEH5), the most "central" GCM (CSMK3), and three other GCMs that preserve as much uncertainty as possible due to between GCM differences (HadGEM, GFCM21 and IPCM4) (see Deliverable 3.2).

Projections of Europe-wide area-average temperature change range from 1.1 to 4.9^{o}C in winter and 1.0 to 3.6^{o}C in summer in the 2050s. Projections for precipitation change range from increases of between 1.1 and 12.5% in winter and decreases of between 2.0 and 29.5% in summer. The pattern of temperature and precipitation changes differs according to the GCM. In winter, most GCMs have a north to south or northeast to southwest pattern in temperature change with the most severe changes occurring in the north/northeast of Europe. The CSMK2 model shows the greatest increases in these areas. In summer, the pattern of temperature change is reversed with the most severe increases in temperature occurring in southern Europe in all GCMs, except IPCM4. GFCM21 exhibits the greatest changes and a strong north-south gradient whereas HadGEM shows a more even spatial distribution. For precipitation in winter, all GCMs show a north to south gradient with increases in precipitation in the north and decreases in the south. HadGEM is relatively drier than the other GCMs in northern and central Europe, whilst GFCM21 is driest in southern Europe. In summer, the GCMs also show a north to south pattern in precipitation changes although this is less clear in the IPCM4 model. GFCM21 stands out as being particularly dry in large parts of southern and continental Europe, whilst IPCM4 is the least extreme.

2.2.2 Socio-economic scenarios

For the socio-economic scenarios, the user can select one of four scenarios that were developed by stakeholders in a series of three participatory scenario workshops within the CLIMSAVE project (see Deliverables 1.4a and 3.3). The scenarios are organised along two dimensions: "Economic Development" and "Solutions by Innovation". The scenarios cover a range of aspects including social, economic, cultural, institutional and political developments in a set of integrated future outlooks.

The most prosperous future scenario, combining high levels of innovation and gradual economic development is We are the World (WRW); where effective governments change the focus from GDP to well-being, which leads to a redistribution of wealth, and thus to less inequality and more (global) cooperation. In comparison, governments in the Icarus scenario focus on short-term policy planning, which together with a gradually stagnating economy, leads to the disintegration of the social fabric and to a shortage of goods and services. The Should I Stay or Should I Go (SoG) scenario is characterised by actors failing to address a rollercoaster of economic crises, which leads to an increased gap between rich and poor, to political instability and to conflicts. In this scenario most citizens live in an insecure and unstable world. The Riders on the Storm (Riders) scenario is equally hit hard by continual economic crises. However, actors successfully counter the situation through investment in renewable energies and green technologies. In this scenario Europe is an important player in a turbulent world.

2.3 Regions

Both sensitivity and scenario analyses focus on five spatial extents including the four regions of Europe (north, south, east and west) and the full European extent. The boundaries used are based on river basins rather than political units. Hence, some countries (e.g. France, Germany, Slovakia and Hungary) are split between regions by cross-border catchments (Figure 1).

Figure 1: The four European regions: west - Austria, Belgium, Czech Republic, Denmark, France, Germany, Hungary (west), Ireland, Luxembourg, Netherlands, Slovakia (west), Switzerland, UK; **south** - Bulgaria (southwest), Greece, France (Mediterranean coast), Italy, Portugal, Spain, Slovenia; **east** - Bulgaria, Estonia, Germany (extreme northeast), Hungary (east), Latvia, Lithuania, Poland, Romania, Slovakia (east); **north** - Norway, Sweden, Finland.

2.4 Indicators

The CLIMSAVE IA Platform outputs a large number of variables representing each of the six sectors. A number of key indicator variables were selected from these on which to focus the sensitivity and scenario analysis. The agricultural and forestry sectors are so inter-related in their response to both climatic and socio-economic drivers that they are addressed together in relation to other land use indicators.

3. Sensitivity Analysis

3.1 Sensitivity methodology

Sensitivity analysis is used to understand the relationships between drivers, as represented by the IA Platform input variables, and sectoral responses, as represented by the selected IA Platform output variables (Table 1). A “One-Driver-at-a-Time” (ODAT) sensitivity analysis approach was implemented where a single driver is modified by a set step and all remaining input variables are maintained at their baseline settings. For this, 24 key drivers were identified and used within the sensitivity analysis. For each driver the full range of values available within the IA Platform was identified and the Platform was run with the driver variable set at the maximum, minimum and a range of settings between these two extremes: for the majority of drivers 5-7 steps were used including the minimum and maximum (Table 2).

Table 1: IA Platform output variables selected as indicators for the sensitivity and scenario analyses.

Sector	Selected indicator	Definition	Sensitivity	Scenario
Urban	Artificial surfaces	Relative change in artificial surfaces compared to baseline	✓	✓
Flooding	People flooded in a 1 in 100 year event	The total population flooded by a 1 in 100 year flood event	✓	✓
Land-use related	Food production per capita	Total food produced	✓	✓
	Intensive farming	Percentage of grid cell that is allocated to the land use "intensive farming"		✓
	Extensive farming	Percentage of grid cell that is allocated to the land use "extensive farming"		✓
	Unmanaged land	Percentage of grid cell that is not allocated to any of the other land uses (farming, forestry, urban).		✓
	Forest area	Area of managed/unmanaged forestry within a grid cell		✓
	Total timber production	Total timber produced	✓	
	Land use intensity	Indicator reflecting the intensity of land use. Intensity is seen to increase from urban to intensive agriculture to extensive agriculture to forest to unmanaged land.		✓
	Land use diversity	Representation of multi-functionality of the landscape based on the Shannon Index	✓	
Biodiversity	Biodiversity vulnerability index	Change relative to baseline in the number of species present for a mixed representative species group in terms of appropriate habitat and climate-space.	✓	✓
Water-related	Water exploitation index	Water withdrawal to availability ratio	✓	✓
	Irrigation uptake	The amount of irrigation used		✓

Table 2: List of climate and socio-economic change driver variables and associated input values selected for the sensitivity analysis.

Group	Driver		Full driver name (*units*)	Baseline default settings	Selected driver values			
					Steps	Min	Step size	Max
CLIMATE CHANGE DRIVERS:								
Climate	1	[Temp]	Annual temperature change (°C)	0	6	0	1	6
	2	[WPrec]	Winter precipitation change (%)	0	5	-50	20	50
	3	[SPrec]	Summer precipitation change (%)	0	5	-50	20	50
	4	[CO2]	CO2 concentration (ppm)	350	7	350	50	700
	5	[SLR]	Sea level change (m)	0	8	0	0.25	2
SOCIO-ECONOMIC CHANGE DRIVERS:								
Social	6	[Population]	Population change (%)	0	5	-50	20	50
	7	[StructChange]	Water savings due to behavioural change (%)	0	5	-50	20	50
	8	[Ruminant]	Change in dietary preference for beef and lamb (%)	0	5	-100	40	100
	9	[NonRuminant]	Change in dietary preference for chicken and pork (%)	0	5	-100	40	100
	10	[GreenRed]	Household externalities preference (#)	3	4	1	1	5
Economy	11	[GDP]	GDP change (%)	0	11	-20	20	200
	12	[OilPrice]	Change in oil price (%)	0	5	0	80	400
	13	[FoodImports]	Change in food imports (%)	0	5	-20	20	80
Environment	14	[SetAside]	Set aside (%)	3	5	0	2	10
	15	[ReduceDiffuse]	Reducing diffuse source of pollution from irrigation (-)	1	5	0.5	0.3	2
	16[a]	[ForestMgmt]	Forest management (-)	Optimum	3	[Options – see below]		
Technology	17	[TechFactor]	Change in agricultural mechanisation (%)	0	5	0	20	100
	18	[TechChange]	Water savings due to technological change (%)	0	6	-75	25	75
	19	[YieldFactor]	Change in agricultural yields (%)	0	6	-50	25	100
	20	[IrrigationEfficiency]	Change in irrigation efficiency (%)	0	6	-50	25	100
Policy	21[b]	[DevCompaction]	Compact vs sprawled development (-)	Medium	3	[Buttons – see below]		
	22[b]	[CoastAttract]	Attractiveness of coast (-)	Medium	3	[Buttons – see below]		
	23[c]	[WaterDistriRule]	Water demand prioritisation (-)	Baseline	4	[Options – see below]		
	24[d]	[FloodProtection]	Level of flood protection (-)	Minimum	3	[Buttons – see below]		

Note:
[a] Forest management (Menu Options): [1] Optimum, [2] Un-evenaged, [3] Even-aged (considering 5 tree species: (1) Pinus sylvestris, (2) Pinus halepensis, (3) Pinus pinaster, (4) Quercus ilex, & (5) Fagus sylvatica)
[b] Compact vs sprawled development /Attractiveness of coast (Button Options): [1] Low, [2] Medium, [3] High
[c] *Water demand prioritisation (Menu Options)*: [1] Baseline, [2] Prioritising food production, [3] Prioritising environmental needs, [4] Prioritising domestic/industrial needs
[d] *Level of flood protection (Button Options)*: [1] No protection, [2] Minimum, [3] Maximum

The data produced was analysed to determine four aspects of sensitivity for each sector: (i) *sectoral interdependence*: the extent to which the sector is sensitive to changes in other sectors; (ii) the *key drivers* that determine sensitivity of the sectoral indicator; (iii) the *level of contribution* each driver has on the sensitivity of the sectoral indicator; and (iv) the *direction of influence* of each driver (whether an increase in the driver contributes to an increase or decrease in the sectoral indicator).

The first aspect, sectoral interdependence, was determined with reference to the IA Platform network. Sensitivity to drivers was classified into three classes: *direct*, *indirect* and *combined* with reference to the chain of variables between the input driver variable and the output indicator variable. Drivers were classified as having "direct sensitivity" when the driver variable was a direct input to the model from which the sectoral indicator was output. For example, sea-level rise is a direct input variable into the flood model and directly affects the relevant sectoral indicator, the number of people flooded. "Indirect sensitivity" occurs where a sectoral indicator shows sensitivity through the interconnected meta-model framework. For example, the input driver "food imports" has an indirect impact on the biodiversity sector through its impacts on land use patterns which in turn affect habitat availability and thereby the biodiversity vulnerability index - the selected sectoral indicator. "Combined sensitivity" occurs where the driver leads to both direct and indirect sensitivity: again in a biodiversity context, changes in precipitation are a good example. Precipitation change impacts the suitability of climate space for species – a direct sensitivity; but it also has an indirect impact by influencing the suitability of land use for different crop types, which in turn influence available habitat – an indirect affect.

The second aspect, the key drivers for each sector, was identified as all drivers to which the sectoral indicators showed any sensitivity. The third aspect, the level of contribution, was calculated by using iterative non-linear least squares regression (Brown 2001; Kemmer and Keller 2010) to fit a standardised regression line to the relationship between drivers and the sectoral indicators of the form Indicator = a * Driver^n. The iteration is performed using the SOLVER macro function in Microsoft Excel, which uses the robust and reliable Generalised Reduced Gradient (GRG) algorithm. A detailed description of the evolution and implementation of this algorithm can be found in Lasodn et al. (1978) and Smith and Lasdon (1992). The linear coefficient of the line (a) was used as an indicator of the strength of the relationship. Thresholds were then applied to this value in terms of % change from baseline to classify the strength into three classes: "insignificant", "weak" and "strong". Changes between -5% and +5% were classified insignificant, and thresholds for "weak" and "strong" were determined by the sectoral experts with reference to the results. The final aspect, the direction of influence was interpreted for all key drivers (i.e. for those which showed some response) from graphs of the relationship between drivers and indicators, and the coefficient of the regression lines. Where relationships were present, the majority of key drivers showed either "positive" or "negative" trends, however, mixed-trends (such as "n-shaped" and "u-shaped" trends) were also identified and recorded.

3.2 Sensitivity results

Figure 2 shows significant differences between the sectors. The urban and flooding sectors are sensitive to a small number of driving variables (5 or 6), in contrast to the remaining sectors which are influenced by a large number of variables (18-24). This suggests that the urban and flooding outputs are considerably less sensitive to cross-sectoral influences. The urban sector in particular is only driven by direct, socio-economic drivers and is entirely independent to the other models. This is expected as it is at the top of the modelling chain. It is also notable that change in artificial surfaces (the sectoral indicator for urban) is entirely independent from climatic drivers. Instead it is strongly driven by GDP with a notable influence from population increase.

	URBAN			FLOODING			FOREST			LAND USE			BIODIVERSITY			WATER			Sectoral Summary			
CLIMATE DRIVERS:																			I	W	S	Score
1 Temp				-	I	W	↓	C	L,Fo	↘	C	L,Fo	↑	C	L,Fo	↑	C	L	5	4	3	12
2 WPrec				↗	I	W	↑	C	L,Fo	↗→	C	L,Fo	↓	C	L,Fo	↓	C	L	5	5	4	14
3 SPrec				↗	I	W	↑↘	C	L,Fo	↘	C	L,Fo	↓	C	L,Fo	↓	C	L	5	5	3	13
4 CO2							↑	C	L,Fo	↓	C	L,Fo	↗	I	L,Fo	+	I	L,Fo	4	3	2	9
5 SLR				↑	DIRECT		-	I	L,Fl	-	I	Fl	+	I	L,Fl	-	I	L,Fl	5	1	1	7
SOCIO-ECONOMIC DRIVERS:																			I	W	S	0
6 Population	↗	DIRECT		↑	C	Fl,U	↓	I	L	↑→	DIRECT		↓↗	I	L	↑	C	L,W	6	6	5	17
7 StructChange																↘	DIRECT		1	1	0	2
8 Ruminant							↓	I	L	↗	DIRECT		+	I	L	+	I	L	4	4	0	8
9 NonRuminant							-	I	L	↗→	DIRECT		↘	I	L	↘→	I	L	4	3	0	7
10 GreenRed	+	DIRECT					-	I	L,U	+	I	U				-	I	L,U	4	0	0	4
11 GDP	↑	DIRECT					↘	I	L,U	↘	I	U	+	I	L,U	↑	C	L,U,W	5	4	2	11
12 OilPrice							↘	I	L	↗	DIRECT		+	I	L	↗	I	L	4	3	0	7
13 ImportFactor							↑	I	L	↓	DIRECT		↗	I	L	↘	I	L	4	4	2	10
14 SetAside																~	I	L	1	0	0	1
15 ReduceDiffuse							↘	I	L	+	DIRECT		-	I	L	↗	I	L	4	2	0	6
16 ForestMgmt							↘	I	Fo	+	I	Fo	+	I	L,Fo	+	I	L,Fo	4	1	0	5
17 TechFactor							↘	I	L	↘	DIRECT		+	I	L	-	I	L	4	2	0	6
18 TechChange																↓	DIRECT		1	1	1	3
19 YieldFactor							↑→	I	L	↘	DIRECT		↗	I	L	↓↗	I	L	4	4	2	10
20 IrrigationEfficiency							↘	I	L	+	DIRECT		+	I	L	↗	I	L	4	2	0	6
21 DevCompaction	~	DIRECT					~	I	L,U	~	I	U				~	I	L,U	4	0	0	4
22 CoastAttract	+	DIRECT					-	I	L,U	+	I	U				-	I	L,U	4	0	0	4
23 WaterDistriRule							-	I	L,W	-	I	W	+	I	L,W	-	C	L,W	4	0	0	4
24 FloodProtection				↓	DIRECT		+	I	L,Fl	~	I	Fl	-	I	L,Fl	+	I	L,Fl	5	1	1	7
Total Drivers	5			6			21			21			18			24						
Significant Drivers	2			5			14			12			9			13						
Significant Direct Drivers	2			2			0			7			0			2						

		Level of contribution		
		Insignificant	**Weak**	**Strong**
Trend	Positive	+	↗	↑
	Negative	-	↘	↓
	Mixed	~	Combinations of above	

Sensitivity	
Direct	DIRECT
Indirect	I
Combined	C
Model chain	U(rban),Fl(ooding), Fo(rest), L(and use), B(iodiversity), W(ater)

Figure 2: Overview of the sensitivity analysis highlighting the relationship between drivers and sectoral indicators at the European scale. Sectoral summary counts the number of sectors with relationships identified as Insignificant (I), Weak (W) or Strong (S). The score is the sum of these values (to a maximum of 18); drivers with higher scores are more relevant to a greater number of sectors.

The flood sector is shown to be sensitive to five main drivers. Two drivers are direct inputs to the flood model: sea-level rise, which has a strong positive influence on flooding, and flood protection, which has a strong negative influence on flooding. Winter and summer precipitation result in indirect impacts; they contribute to sensitivity by modifying river flows which are output from the water model. Finally, population change leads to combined sensitivity, having a direct influence on the number of people flooded (if there are more people there would be more people to be flooded) and indirectly via influencing the urban growth model (if there are more people, there will be more urban growth).

The forest sector is most strongly driven by climatic drivers, and indirect drivers that influence timber production via changes in the land use model (population change, food imports and food yields). In terms of the climatic drivers, increases in precipitation and CO_2 are shown to lead to increases in forest productivity, whilst increases in temperature reduce productivity. These climatic drivers fit with expectations with regard to timber production (increasing CO_2 would lead to increases in timber yield for example), but they will also influence other sectors, such as agricultural food production which will in turn lead to knock-on effects on the relative profitability of forest and agriculture sectors, which will in turn have an impact on forest production. The relationships seen with the socio-economic drivers reflect this as well: increased food imports lead to a reduced need for cultivation; this in turn reduces the profitability of agriculture relative to forestry and allows timber production to increase. An increase in crop yield has a similar effect: greater yields mean that less agricultural area is needed to produce the same amount of food, thus reducing competition for land use and improving forestry. Increasing population has a negative effect on forestry for the opposite reason – it increases the demand for food and so reduces forestry's relative profitability.

Land use diversity is driven by 14 significant drivers - four climatic and 10 socio-economic. As land use diversity is greatest in scenarios where there is a broad mix of land uses within a grid cell it is positively influenced by any changes that lead to new land uses becoming present in a grid cell – providing that the changes are not at the expense of the total removal of another land use. Figure 2 shows that land use diversity is sensitive in a positive direction to factors that encourage agriculture to spread more widely into new areas. These include population increase, changing food preferences (ruminant/non-ruminant) and increased winter precipitation. Conversely, there is sensitivity in a negative direction to factors that make it easier to produce food in less area (such as improvements in agricultural technology or yields); factors that decrease the need for food production (e.g. food imports); factors that make it harder for agriculture to spread (hotter climates) and factors that make other land uses more competitive (increase in CO_2, c.f. forest sector above). Whilst the major driver behind land use diversity is agricultural expansion/contraction the total loss of forestry that occurs in some scenarios also leads to some sensitivity: the sensitivity identified to summer precipitation is a result of the total loss of forestry in some areas of Europe – leading to a notable reduction in diversity.

Much like the forestry and land use diversity indicators, the nine key drivers to which the Biodiversity Vulnerability Index shows the greatest sensitivity reflect climatic influences and factors that influence agricultural land use. The biodiversity model combines bioclimatic envelope modelling, which identifies appropriate climate space for a selected species group, with habitat masks output from the land use model. As such, the increase of biodiversity vulnerability with increasing temperature and the decrease of vulnerability in wetter conditions is expected to reflect not only shifting patterns of climatic suitability for the species in question, but also to influence the availability of appropriate habitat (arable fields, forests, wetlands). The influence of population change on land use – particularly through its influence on agriculture (and thus the availability of habitat for some arable-based species) leads to the identified positive sensitivity. Similar to land use diversity, the more cells with some arable present, the more habitat for the arable loving species and the less biodiversity vulnerability: unless that land use change comes at the expense of the removal of another key land use (such as forestry). Again, factors such as agricultural yield and agricultural technology which decrease the amount of space required to produce the same amount of food lead to a restriction in arable habitat and consequently increase biodiversity vulnerability.

4. Scenario analysis

The identification of drivers of change which are particularly important for different sectors or cross-sectoral interactions through the sensitivity analysis is important for understanding the effects of combined climate and non-climate drivers, as represented by the climate and socio-economic scenarios, on impact indicators from the IA Platform.

4.1 Scenario methodology

The CLIMSAVE IA Platform was run for 50 climate change and socio-economic change scenarios for the 2050s time-slice to explore the effects of climate change uncertainties on cross-sectoral impacts. The scenario combinations can be categorised into three groups:

1. Climate scenarios for the five GCMs combined with a low emissions scenario (B1) and low climate sensitivity (5 runs);
2. Climate scenarios for the five GCMs combined with a high emissions scenario (A1) and high climate sensitivity (5 runs); and
3. Climate scenarios (10 runs above) combined with the four socio-economic scenarios (40 runs).

Six indicators were used in the sensitivity analysis to provide a broad assessment of the effects of different climate and non-climate drivers on the six CLIMSAVE sectors. To better understand the impacts resulting from the application of the climate and socio-economic scenarios, an additional five indicators were selected. Forest production was replaced with forest area to provide a better fit with the other land use indicators (all five key land uses are represented, urban (as artificial surfaces), forest (as forest area); intensive and extensive agriculture and unmanaged land (which includes all land not in any of the other land use classes). With this combination it was no longer necessary to include land use diversity. However, land use intensity was added as an indicator to highlight the impacts of changing agricultural patterns identified as significant within the sensitivity analysis.

In summary: each scenario run was analysed for 11 sectoral indicators: (1) area of artificial surfaces; (2) number of people flooded in a 1 in 100 year event; (3) food production; (4) area of intensive farming; (5) area of extensive farming; (6) forest area; (7) area of unmanaged land; (8) land use intensity index; (9) biodiversity vulnerability index; (10) water exploitation index; and (11) irrigation uptake.

Each indicator was analysed for the whole of Europe and the four catchment-based regions for northern, western, eastern and southern Europe (Figure 1). For each combination of indicator, scenario and region summary statistics were computed for the median and the 5th, 25th, 75th and 95th percentiles. A t-test was also performed on each indicator in each scenario and region to determine if the indicator was statistically different from its baseline using a paired t-test using a $P<0.05$ significance threshold. The t-test results were used to calculate the percentage of indicators where the mean was statistically different from baseline for each scenario/region combination. Mean difference from baseline was also calculated for each indicator and used to calculate the minimum and maximum change from baseline for different combinations of scenarios.

4.2 Scenario results

4.2.1 Statistical significance of impacts

For the runs based on just climate change scenarios, 82.7% of indicators are statistically different from their baseline counterparts at the European scale (Table 3). Those found not to be statistically significantly different include all the scenarios for the urban indicator which has no climate-driven response, many of the scenarios for food production and a single scenario for biodiversity. Many of the runs also showed significant differences from baseline at the regional scale: northern and western Europe are the most similar to baseline followed by eastern Europe, with southern Europe showing the largest changes where only 9.1% of indicators have a statistically similar mean to baseline. The factors driving this differ by region, with different indicators remaining statistically similar as a result of climate: in western Europe, it is food production and intensive farming; in eastern Europe, food and biodiversity; in northern Europe, irrigation and flooding. In southern Europe, all indicators are statistically different from baseline, with the exception of urban areas.

Table 3: Average percentage of indicators that are statistically significantly different from the baseline for the climate-only scenarios and the combined climate and socio-economic scenarios.

	Climate scenarios	Climate & socio-economic scenarios			
		Riders	WRW	SoG	Icarus
Europe	82.7	88.2	90.0	90.9	79.1
Western Europe	84.5	90.0	87.3	89.1	86.4
Southern Europe	90.9	90.0	89.1	90.9	82.7
Eastern Europe	87.3	88.2	90.0	90.9	82.7
Northern Europe	83.6	90.0	90.9	83.6	90.0

For the runs based on combined climate and socio-economic scenarios, Icarus stands out as having the lowest proportion of outcomes statistically different to baseline at the European scale. This is in large part due to the fact that unlike the other scenarios there is considerably less change in the “number of people flooded” indicator for Icarus, driven by the fact that Icarus is the only socio-economic scenario that sees a decline in population. The other three scenarios have relatively similar high levels of difference from baseline, but with regional differences. SoG has the least statistically different scenarios in northern Europe; Riders has the least in eastern Europe and WRW has the least in western Europe. The reasons for this include the fact that in the SoG scenario there are not statistically significant differences in flooding or extensive farmland in one or more scenarios in the north, and in irrigation in the west. For WRW northern Europe is the only region where there all scenarios are statistically different from baseline in terms of food production; additionally western Europe shows less statistically different scenarios in terms of land use intensity and intensive farming. The Riders scenario has relationships that are not statistically different from baseline in terms of the intensity index (in eastern and northern Europe) and intensive farming (in western and southern Europe).

4.2.2 Sectoral changes at a European scale

At the European scale it is clear that the different sectors respond very differently to different drivers. Table 4 provides a statistical summary of the mean change values of each indicator across the scenarios; it highlights the maximum and minimum values produced in both (i) climate only and (ii) combined climate and socio-economic scenarios. However, focusing only on changes in the central tendency hides a lot of change that takes place in the distributions, particularly at the extremes. To address this Figure 3 extends the analysis and summarises the full distribution of the indicators as box and whisker plots focusing on the median, 5th, 25th, 75th and 95th percentiles of the distribution for eight indicators in the 10 climate scenarios runs (and summarised across all these runs as 2050 BL) and 40 combined climate and socio-economic scenario runs (summarised for the 10 runs undertaken for each of the four socio-economic scenarios). Further summaries based on changes in the 25th and 75th percentiles are given by region in Figure 4. Box and whisker plots for the indicators and scenarios for the four regions as well as Europe as a whole are provided in Appendix A.

Urban sector: area of artificial surfaces

The amount of artificial surfaces within a scenario is driven solely by changes within the socio-economic scenarios; there is no influence of climate. As such Figure 3 shows identical histograms for baseline and 2050BL and the 10 climate scenarios all have the same distribution. As with the sensitivity analysis, the key drivers on urban growth are population growth and GDP. WRW shows the most growth as both GDP and population growth are high. The second utopian scenario, Riders, also shows higher levels of artificial surfaces as it has high GDP and moderate population growth. The dystopian scenario, SoG, has high population growth, but low GDP and as such shows only limited growth in eastern Europe (Figure 3). In contrast, the Icarus scenario shows no trends >5% at either the 25th or the 75th percentile (Figure 3) due to the fact that whilst GDP stays at current levels, population is in decline in this scenario.

From a regional perspective, in both Riders and WRW the changes in northern and western Europe are proportionally greater (>50% increase) than those in southern and eastern Europe (5-50%; Figure 4). However, very different magnitudes of growth are identified: in northern Europe there is a small increase from a low baseline, e.g. the 75th percentile increases from 0.72% to >1.1%, whereas in western Europe the increase is from 7.4% (due to several large cities, such as London, in this region) to >10%. In southern Europe, the 75th percentile increases by ≥29% from a baseline of 2.93%. Eastern Europe, however, shows very little urban growth; despite having a high baseline 75th percentile (5.6%); this increases by <10% even in the utopian scenarios: this is a factor of the lower GDP in the eastern countries.

Table 4: Maximum and minimum values of mean change from baseline for the 2050s. Values are presented by indicator and region for: (a) climate scenarios using baseline socio-economic values (i.e. driven by climate alone: marked “CLIMATE”, light grey columns); and (b) averaged across the four socio-economic scenarios (marked “SOCIO”, white columns). Darker grey highlights are used to identify indicators where the maximum and minimum trends are in different directions; where this is not the case the direction of the trend may be seen as robust in the context of the scenarios.

	Europe	Europe	Europe	Europe	West	West	West	West	South	South	South	South	East	East	East	East	North	North	North	North
	CLIMATE	CLIMATE	SOCIO	SOCIO	CLIMATE	CLIMATE	SOCIO	SOCIO	CLIMATE	CLIMATE	SOCIO	SOCIO	CLIMATE	CLIMATE	SOCIO	SOCIO	CLIMATE	CLIMATE	SOCIO	SOCIO
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Artificial surfaces (%)	0.0	0.0	0.0	1.2	0.0	0.0	0.0	2.5	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.6
People flooded (1000s people)	0.5	0.9	-0.2	2.7	1.7	2.6	0.5	5.3	0.5	1.1	-0.2	2.5	-1.0	-0.4	-1.9	7.8	0.1	0.2	0.0	0.6
Water Exploitation Index (-)	0.0	0.2	0.0	0.3	0.0	0.1	-0.1	0.2	0.1	0.6	0.1	0.7	0.1	0.3	0.0	0.4	0.0	0.0	0.0	0.0
Irrigation usage (10^3 m^3/yr)	0.5	0.9	0.2	2.4	0.0	0.3	0.0	3.1	1.7	2.7	0.4	5.3	0.7	1.5	0.3	4.0	0.0	0.0	0.0	0.0
Biodiversity VI (-)	0.0	0.1	0.0	0.1	0.0	0.2	0.0	0.3	0.2	0.4	0.1	0.5	0.0	0.3	0.0	0.4	-0.4	-0.1	-0.4	0.0
Food production (cal/day)	228.4	280.2	199.2	353.0	327.9	431.2	302.4	502.5	275.5	337.0	197.8	397.7	153.8	236.1	156.8	349.9	113.5	209.2	101.5	286.3
Intensively farmed (%)	-3.6	-0.6	-5.5	26.7	-5.7	1.9	-9.0	23.7	-19.0	-9.1	-20.7	21.4	-10.2	-6.0	-20.5	28.1	5.4	10.0	3.6	31.7
Extensively farmed (%)	-7.1	-2.0	-7.8	5.3	0.8	7.7	-3.8	7.2	-8.3	4.2	-9.6	7.2	1.6	8.3	-3.5	12.4	-20.3	-17.9	-20.5	4.6
Forest area (km^2)	-1995.4	-1389.5	-4159.8	-1451.7	-2999.2	-1799.0	-4340.3	-1822.0	-1768.4	-904.9	-2977.2	-959.7	-1799.5	-1072.6	-4875.4	-653.8	-1817.3	-1059.8	-4279.7	-945.6
Unmanaged land (%)	10.7	20.5	-1.5	22.5	3.5	14.2	-0.1	16.4	9.3	33.9	-0.2	33.4	4.9	15.0	-0.2	25.7	19.0	22.3	-4.4	26.2
Intensity index (-)	-0.1	0.0	-0.1	0.1	-0.1	0.0	-0.1	0.1	-0.2	-0.1	-0.2	0.1	-0.1	0.0	-0.2	0.1	-0.1	-0.1	-0.1	0.2

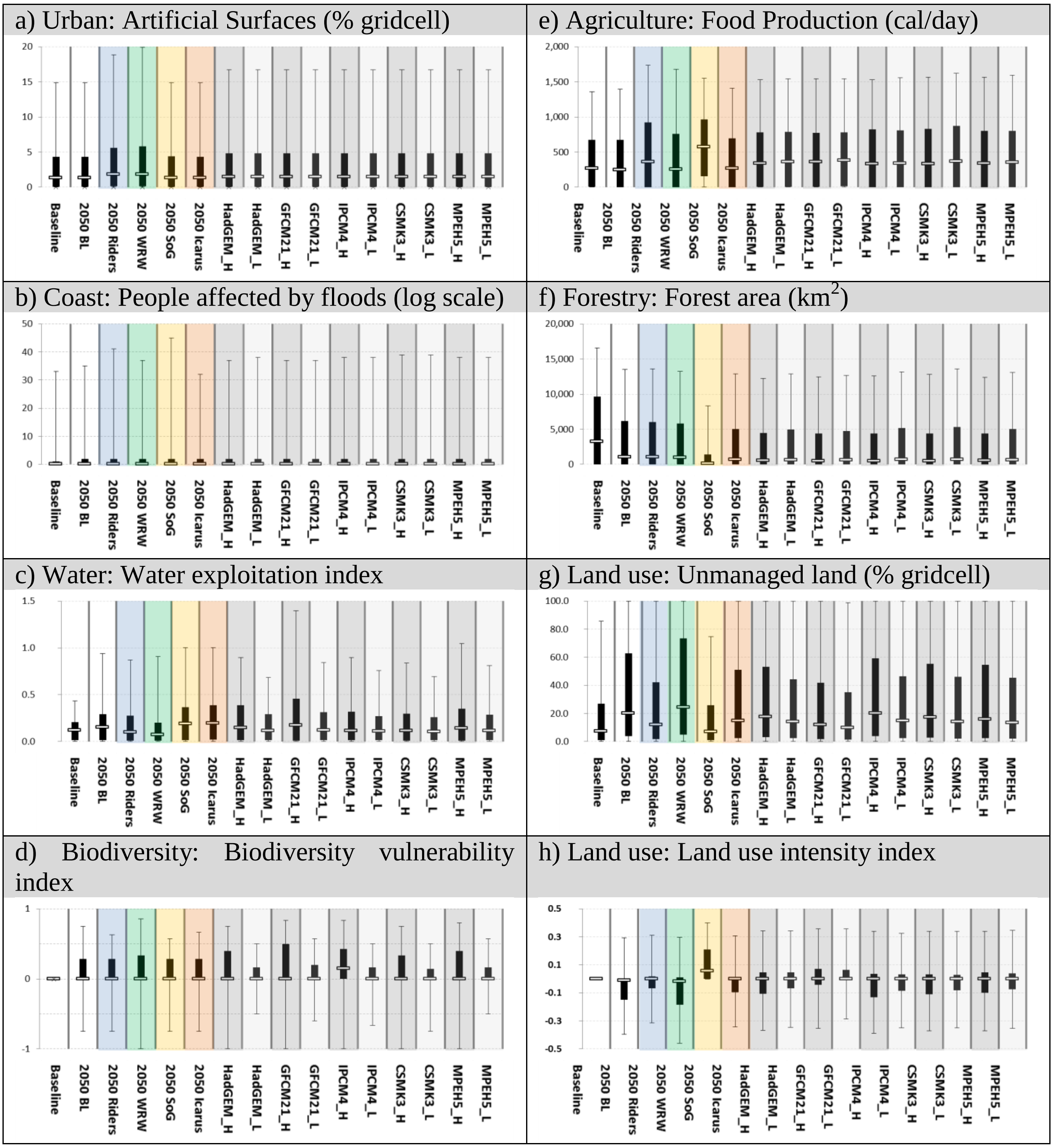

Figure 3a-h: Box and whisker plots for eight indicators for baseline, 2050s climate with no socio-economic scenarios (2050 BL), the four socio-economic scenarios (2050 Riders, WRW, SoG and Icarus) and for the Low (_L) and High (_H) emissions scenarios of the five climate models (HadGEM, GFCM21, IPCM4, CSMK3 and MPEH5). The whiskers show the 5th and 95th percentiles whilst the boxes show the 25th and 75th percentiles. The median is marked with a white dash in the centre of the box. Note for scaling reasons that values may extend off the displayed graph.

	2050 BL					2050 Riders					2050 WRW					2050 SoG					2050 Icarus				
	Eu	N	W	E	S	Eu	N	W	E	S	Eu	N	W	E	S	Eu	N	W	E	S	Eu	N	W	E	S
Artificial surfaces (%)	∘	∘	∘	∘	∘	**+**	**↑**	**↑**	**+**	**+**	**+**	**↑**	**↑**	**+**	**+**	∘	∘	∘	**+**	∘	∘	∘	∘	∘	∘
People flooded (1000s people)	↑	∘	+	↑	↑	↑	∘	+	↑	↑	↑	∘	+	↑	↑	↑	∘	+	↑	↑	↑	∘	**∘**	↑	↑
Water Exploitation Index (-)	↕	-	+	+	↑	↕	-	**-**	**↕**	↑	**-**	-	**-**	**↓**	↑	**↑**	**+**	**↑**	+	↑	**↑**	**+**	**↑**	+	↑
Irrigation usage (m³/yr)	↑	∘	∘	-	↑	↑	∘	**↑**	**↑**	↑	↑	∘	**↑**	**+**	↑	**∘**	∘	∘	**↓**	↑	↑	∘	**↑**	**↓**	↑
Biodiversity VI (-)	+	-	+	+	↑	+	-	+	+	**+**	+	-	+	+	↑	+	-	+	+	**+**	+	-	+	+	**+**
Food production (cal/day)	↓	↑	-	>	↓	**↕**	**+**	**+**	**↕**	**↕**	**↕**	↑	-	**↓**	**↕**	**↑**	↑	**↑**	**↑**	**↑**	↓	**∘**	**+**	**-**	↓
Intensively farmed (%)	∘	↑	-	+	↓	**+**	**∘**	**+**	+	**-**	**-**	↑	-	**↓**	↓	**↑**	↑	**↑**	**↑**	**↑**	**+**	**∘**	**↑**	+	↓
Extensively farmed (%)	↓	↓	↑	↓	↓	**-**	↓	↑	**↑**	↓	↓	↓	**↕**	↓	↓	**-**	**+**	**-**	↓	↓	**-**	↓	↑	**+**	↓
Forest area (km²)	↓	-	↓	+	↓	↓	-	↓	+	↓	↓	-	↓	+	↓	↓	**↓**	↓	**↓**	↓	↓	-	↓	+	↓
Unmanaged land (%)	↑	↑	↑	↓	↑	↑	↑	↑	↓	↑	↑	↑	↑	**↕**	↑	**∘**	**-**	**-**	↓	**∘**	↑	↑	↑	↓	↑
Intensity index (-)	-	-	-	-	-	-	-	**+**	**∘**	-	-	-	-	-	-	**+**	**+**	**+**	**+**	**+**	-	-	**+**	-	-

Symbol	Change in distribution
↑	Increase >50% in either the 25th or 75th percentile with a non-negative change in the other
+	Increase >5% in either the 25th or 75th percentile with a non-negative change in the other
∘	Change < ±5% in both the 25th or 75th percentile
-	Increase >5% in either the 25th or 75th percentile with a non-positive change in the other
↓	Decrease >50% in either the 25th or 75th percentile with a non-positive change in the other
>	Decrease > 5% in 75th percentile and Increase > 5% in 25th percentile – contracting distribution
↕	Increase > 5% in 75th percentile and decrease > 5% in 25th percentile – widening distribution

Figure 4: Cross-sectoral summary of changes in the 25th and 75th percentiles of distributions for Europe and the four regions for the climate-only scenarios with baseline socio-economic scenarios (2050 BL) and the combined climate and socio-economic scenarios (divided into Riders, WRW, SoG and Icarus). Differences from the 2050 BL for the combined climate and socio-economic scenarios are highlighted in bold and boxed. Colour coding of symbols is simply to help distinguish between the regions (i.e. Europe = black; northern Europe = blue; western Europe = green; eastern Europe = yellow; and southern Europe = red).

Coastal sector: number of people flooded in a 1 in 100 year flood event

At the European scale for the majority of locations there is very little change in the number of people flooded; the median is 0 in all scenarios. However, there are changes in the extreme values of the number of people affected by flooding and the 75th percentile increases from 100 to 200 people irrespective of the socio-economic and climatic scenario (Figure 3). At the 95th percentile (the minimum number of people affected by the top 5% of floods) there is notable variation between the socio-economic scenarios: values are higher in the SoG and Riders scenarios, and lowest in the Icarus scenario. This reflects the changes in populations assigned to these scenarios: in SoG, Riders and WRW the population increases by 23, 16 and 5% respectively, whilst in Icarus European population declines by 9%. The flooding indicator is also impacted by the climate scenarios, as evidenced by the small differences in the 95th percentiles notable in Figure 3. As the level of sea-level rise is not influenced by the climate scenarios (only by the emissions scenarios), these differences reflect differences in the levels of fluvial flooding as a result of changing patterns of precipitation in the climate scenarios.

Despite the relatively uniform changes in the 75th percentile at the European scale there are considerable inter-regional differences. Western, eastern and southern European regions generally show significant increases in the numbers of people flooded, whilst northern Europe shows no real change. This reflects patterns of urban development, which in turn are heavily driven by baseline population; with less people and lower population growth in the northern region (Scandinavia).

Land use-related indices: food production, intensive and extensive farming, forest area, unmanaged land and the land use intensity index

Food production increases across both Europe and the regions in terms of the mean change in both climate only and combined climate and socio-economic scenarios (Table 4). The socio-economic scenarios exacerbate both extremes of the indicator distributions. Regionally, western Europe shows the greatest mean increase in food production, whilst northern Europe shows the least.

In terms of the climate only scenarios, the percentiles show that very different impacts are found in the different regions. In northern Europe there is a general increase in the extreme values with the 75th percentile increasing from 8 to 80 calories/day. Conversely, in southern and western Europe both the 25th and 75th percentiles decrease. In eastern Europe the distribution contracts, with an increase in the 25th percentile and a decrease in the 75th percentile, suggesting that extreme values become less present.

The socio-economic scenarios have a significant influence considerably changing food production from its values based on climate alone. SoG is particularly notable as it significantly increases food production at both the 25th and the 75th percentiles in all regions (Figure 3). Conversely, at the European scale Riders shows significant increases in the 75th percentile, but doesn’t show a matching increase in the 25th percentile. As such SoG’s median is considerably higher than all other socio-economic scenarios; however, its 95th percentile is lower than both Riders and WRW. This reflects the scenarios well. SoG is a particularly extreme scenario with a significant increase in population (+23%), but no successful innovation. As a result, agricultural mechanisation increases slowly relative to the other scenarios and “water savings from technological change”, “irrigation efficiency” and “agricultural yields” all decline significantly. These factors lead to a world where food production is the key priority. This has impacts on all other land use sectors and significant increases are noted in terms of the amount of intensive farming and the intensity index. Extensive farming declines in western Europe (replaced by intensive farming), and increases in northern Europe (where it replaces forestry and unmanaged land). Forest cover declines in all areas, particularly in the north and east, and the positive trends in unmanaged land in the north, south and west identified in the climate-only scenarios are absent or negative in all regions as the scenario makes use of all available land to meet the pressing food demand.

Conversely, in the WRW and Riders scenarios population increase is lower (+5% and +16%), and technological innovations lead to improvements in agricultural mechanisation, water savings, irrigation efficiency and agricultural yields. In addition there are dietary changes away from beef, lamb, chicken and pork. These factors combine to put less pressure on the system to produce food. As such, at a European scale both scenarios show mixed trends with some areas producing more food than they are able to within SoG (due to successful innovations), but without the extreme levels of conversion of all other land uses that are seen in SoG. Forest areas are modelled to change in the same way that they do under the climate-only scenario. Unmanaged land shows positive trends in northern, southern and western Europe, particularly in the WRW scenario, and mixed/negative trends in WRW/Riders, respectively, in eastern Europe (where conversion to farmland is taking place). As a result land use intensity generally shows negative trends in WRW or Riders.

It is notable that forest area declines in northern, southern and western Europe in all scenarios (and only slightly increases in eastern Europe in Riders, WRW and Icarus), whilst intensive and extensive agriculture show mixed trends and unmanaged land increases in most scenarios (not SoG) in all regions, but eastern Europe. The decline in forests results from a number of factors. Firstly, profitability: in some scenarios, particularly those as extreme as SoG, forest land is simply not as profitable as food-producing land; in these scenarios trees are replaced by agriculture. Secondly, CO_2 increase: timber yield increases due to increasing levels of CO_2. This means that less forest area is required to produce the same amount of timber. As such profitability is affected and the amount of land required for forests declines. Thirdly, climatic suitability: some areas change in terms of their climatic suitability for the currently planted species. In these cases, the land use can no longer remain forest and is classified as unmanaged land. A combination between these three factors drives the decline in European forests seen in the majority of scenarios and has knock-on impacts for the biodiversity indicator.

Biodiversity: biodiversity vulnerability index (BVI)

In the climate-only scenarios biodiversity vulnerability is modelled to increase in southern, eastern and western Europe, but shows the potential to improve in northern Europe. Trends in terms of the mean are greatest in the south and east (Table 4). In terms of climate drivers, the low emissions scenarios lead to distributions with lower levels of biodiversity vulnerability. There are differences within the climate scenarios: the GFCM21 and IPCM4 climate models result in the greatest vulnerability, but the way the vulnerability manifests is different. For all scenarios, but the high emissions IPCM4, the median value and the 25th percentile are both zero indicating that at least 25% of the data show no change in terms of the total number of species that are vulnerable. However, in the IPCM4 scenario, the 25th percentile is zero and the median suggests that the BVI is greater than 0.2 for over 50% of grid cells (reflecting that 20% of species no longer have appropriate climate-habitat space). Interestingly the GFCM21 scenario has a lower median, but more high values: 25% of its data have a BVI > 0.5. The socio-economic scenarios widen the range between the extremes compared to the runs driven by climate alone. WRW stands out as having the broadest range of values: it has both the highest and the lowest vulnerability in terms of the 5th and 95th percentiles. Conversely, SoG has the least vulnerability in terms of the 95th percentile, but also the least improvement in vulnerability in terms of the 5th percentile.

The strong influence of both climate and socio-economics is expected as biodiversity vulnerability reflects the output of bioclimatic envelope modelling combined with habitat masks from the land use allocation model. Vulnerability increases wherever the climate becomes unsuitable or the appropriate habitat for the species is lost. Impacts beyond those of climate are identified wherever land use changes lead to a key land use (forestry, arable farming, wetlands) being totally removed from a grid cell where a species which is climatically suitable requires that habitat. Thus, SoG's drive towards food production provides positive benefits in terms of broadening the area of Europe with habitat for species associated with arable farming, such as those which rely on cereal field margins. This is partly at the expense of species associated with forests as is evidenced by the 95th percentile of vulnerability in northern Europe being notably greater than any other scenario. In contrast, in the WRW scenario there are significant land use shifts towards "unmanaged land" at the expense of both agriculture and forestry which leads to high biodiversity vulnerability in the WRW scenario.

The index is based on a group of 12 species selected to represent a cross-section of European species from different taxa, regions and habitats. Whilst the choice of these species influences the results, it is clear that changes in habitat are likely to have significant impacts on species already under threat from climate change. The reduction in vulnerability in northern Europe compared to increases in vulnerability elsewhere reflects many of the selected species gaining climate space in the north as it gets warmer and sometimes wetter. The north may, therefore, present opportunities for some of the more mobile threatened southern species.

Water-related indices: water exploitation index and irrigation uptake

In the climate-only scenarios, water exploitation and irrigation use both show positive trends in terms of their mean value, particularly in southern and eastern Europe where water availability is lowest. The socio-economic scenarios exacerbate conditions, extending both maximum and minimum values, but continue to show positive trends in the south and east. Mean difference from baseline in western Europe become mixed with the minimum value showing a decline in water exploitation. Northern Europe shows no change in water exploitation in any scenario.

Climate scenarios have a significant impact on patterns of both water exploitation and irrigation. In all cases the high emissions scenarios lead to more extreme values of the water exploitation index particularly in southern and eastern Europe. The GFCM21 high emissions scenario stands out as a worst-case scenario for water provision particularly in the south and east of Europe: the 25th and 75th percentiles increase from 0.14 and 0.37 at baseline to 0.58 and 1.22 in the GFCM21_H scenario.

For the combined climate and socio-economic scenarios, in general, the utopian scenarios have lower values of the water exploitation index and show higher levels of irrigation, particularly in southern and eastern Europe. Of the two scenarios, Riders uses more irrigation and has higher water exploitation values. Conversely, irrigation usage in SoG and Icarus is low, and only present in the south. Moreover, the water exploitation values are notably higher: in western Europe the 25th percentile of the dystopian scenarios (SoG and Icarus) is greater than the 75th percentiles of the utopian ones (WRW and Riders). These patterns reflect differences in the scenarios, particularly in terms of technological water savings and irrigation efficiency which all increase in the utopian scenarios, but decline in the two dystopian scenarios. "Changes in water efficiency from behavioural change" is also lower in the dystopian scenarios, and negative in Icarus. These factors reflect a division between scenarios: the utopian scenarios, where innovation in terms of water saving, allows greater areas of farmland to be irrigated with less impact on the overall water supply as represented by the water exploitation index; and the dystopian scenarios in which pressures on water supply, and the lack of efficient irrigation, mean that irrigation is a less viable option.

5. Discussion

5.1 Cross-sectoral impacts: which sectors are winners and losers?

From Figure 4 we can see that the sectoral winners and losers vary depending on the socio-economic scenario. In SoG the winner is very much agriculture, all indicators related to food production increase significantly; as a result the other land use sectors forestry and unmanaged land lose land. The water sector also loses as the water exploitation index significantly increases, particularly in western Europe. Conversely, in WRW the water sector is a winner (with a decreasing water exploitation index), and urban growth also increases. Intensive agriculture is a loser, reducing at the European scale, but particularly in the east. The loss of arable habitat in WRW means that it shows a greater increase in biodiversity vulnerability than in the other scenarios – however, within the scenario storyline, the increases in unmanaged land are likely to compensate for this, with the eco-conscious WRW population using these areas to support biodiversity impacted by land use change. Icarus is similar to SoG in that the water sector is a loser, due to failed innovation, but intensive farming and food production do not gain to the extent they do in SoG, nor is there any urban growth reflecting the declining population. There are, however, small improvements relative to SoG in terms of slightly lower biodiversity vulnerability. Icarus, as a result of having no population increase, is also the only scenario in which there are positive changes in people flooded relative to the levels driven by climate. As in WRW, the urban sector is a winner in the Riders scenario. Food production is also better in many European regions than it would be if driven by climate alone, without the dramatic increase in intensive farmland identified in SoG. The water sector is also a winner in the Riders scenario – irrigation increases in western and eastern Europe without significant negative impacts on the water exploitation index. Unlike, WRW which experiences very dramatic land use change towards unmanaged land Riders maintains a greater area of agriculture and as such maintains a greater landscape diversity leading to less notable increases in biodiversity vulnerability in southern Europe than are identified in WRW.

5.2 Methodological limitations

The CLIMSAVE IA Platform is a complex network of interlinked meta-models. It requires careful exploration to identify the relationships between driver variables and outputs particularly when summarised across multiple sectors. One of the most important factors to recognise is that the land use allocation module has an implicit in-built adaptation: food production is prioritised, and if it is not possible to meet European food demand with the existing land use distribution the module autonomously expands agricultural land to meet demand. This means that any driver that has an impact on food demand or agricultural production has a considerable impact on all factors dependant on land use. It also makes scenarios where food provision is de-prioritised, for example to focus on forest products or biodiversity, harder to replicate within the platform. Whilst further extensions of the project may re-consider the prioritisation within the land use model the current system still has considerable utility. Firstly, it is important to note that it is still possible, with an understanding of the system, to compensate for the priority given to food within the existing system. The easiest way to do this is to decrease the proportion of food demand that is not expected to be provided by Europe's land area by increasing "food imports". Secondly, the system does highlight the importance of food security as a key issue driving the future of European land use and the pivotal importance of land use in decision-making: including the considerable knock-on effects on all other sectors.

A second factor to consider is that, so as to be able to run on the web, the biodiversity vulnerability index uses a selected representative species list of 12 species to highlight both changes in land use and climatic impacts (of the 112 available species incorporated in the Platform). The aforementioned priority given to food production has a knock-on impact on the biodiversity index, in that the spread of arable croplands that result in many scenarios leads to a positive impact on biodiversity that might over-represent the importance of arable habitat in contrast to others. Whilst a broadening of the selected species group would likely reduce the risk of this over-representation, the species group does well reflect expected changes in biodiversity, particularly in terms of the regional impacts. The drier areas of Europe are most likely to experience greater pressure on biodiversity, and the north is likely to become an area that provides suitable climate and habitat opportunities for species that suffer from loss of climate-space in the south. It should also be noted that the full list of 112 species in the Platform were selected to focus on species which interact with the other sectors considered in CLIMSAVE and, hence, montane species which might be lost from northern Europe may be under-represented.

5.3 Vulnerability and human well-being

In this deliverable we are considering raw impacts rather than quantifying their contribution to the vulnerability of human well-being. As such, whilst we have identified the winners and losers in terms of sectors, an added dimension – the ability of areas to cope with the impacts – is not included in this analysis. Deliverable 5.2 summarises the approach to vulnerability taken within the CLIMSAVE methodology. It identifies the vulnerability of human well-being to impacts on six key ecosystem services (food provision, water availability, flood regulation, biodiversity, land use intensity and land use diversity). The analysis further reinforces the messages here: the utopian scenarios have greater ability to cope, and as such often exhibit less vulnerability. However, there is no combination of climate and socio-economic scenario that leads to a position where there is no vulnerability in Europe. The cross-sectoral impacts mean that there are scenarios where vulnerability is less or more in particular sectors, but the take-home message remains: tough decisions will need to be made to ensure that the environment is best managed so as to be able to maintain the key ecosystem services needed to support human well-being.

5.4 Scenario uncertainty and the adaptation screen

The scenario analyses draws on the outputs from the "Impacts" screen of the IA Platform for each combination of climate and socio-economic scenario using the default values for each socio-economic driver. A range of values are considered consistent or credible for each socio-economic scenario as represented by the green areas of the sliders in the Impacts screen. For example, the default value of population change in WRW is +5% and the credible range varies from -5% to +15%. A more extreme range is also provided to allow the user to explore wider uncertainty associated with socio-economic drivers, as represented by the yellow area of the sliders. This uncertainty is explored in Deliverable 5.3.

Furthermore, it is possible within the Platform's Adaptation screen to modify the scenario default parameters to reflect adaptation options and whilst the majority of adaptation options modify drivers included within the sensitivity analysis there are some additional adaptation options which are only available on the Adaptation screen (such as increasing protected areas). These factors mean that different scenario-consistent settings can lead to a particular socio-economic scenario resulting in different sectoral sensitivities from those presented here. It is also possible that two scenarios can overlap in terms of driving conditions and, hence, could potentially lead to similar futures. This is a deliberate choice of the CLIMSAVE approach; it is entirely plausible that similar futures may come to arise within different scenario storylines, particularly in terms of the overlap within the utopian scenarios or the dystopian scenarios. As such it is important to clarify here that this analysis focuses on the default scenarios for each socio-economic storyline *prior to adaptation* in an attempt to highlight the key differences between the scenarios. The effects of adaptation on the cross-sectoral impacts are considered in Deliverable 5.3 in terms of different policy archetypes.

6. Conclusions

The purpose of this deliverable is to analyse the outputs from the CLIMSAVE IA Platform to identify those sectors that are the most exposed and sensitive to climate change with particular reference to cross-sectoral linkages. The sensitivity and scenario analysis applied highlights the overwhelming importance of considering cross-sectoral interactions. Figure 4 shows that none of the socio-economic scenarios have positive impacts across all sectoral indicators, in all regions of Europe and that situations in which all sectors are winners will be very difficult, if not impossible, to achieve. Whilst adaptation may offer opportunities to reduce and compensate for some of these cross-sectoral impacts, it is clear that the many contrasting demands of the different sectors will pose considerable challenges for managers and decision-makers. Ultimately, it is likely that there will be sectoral winners and losers in any future – even the utopian ones.

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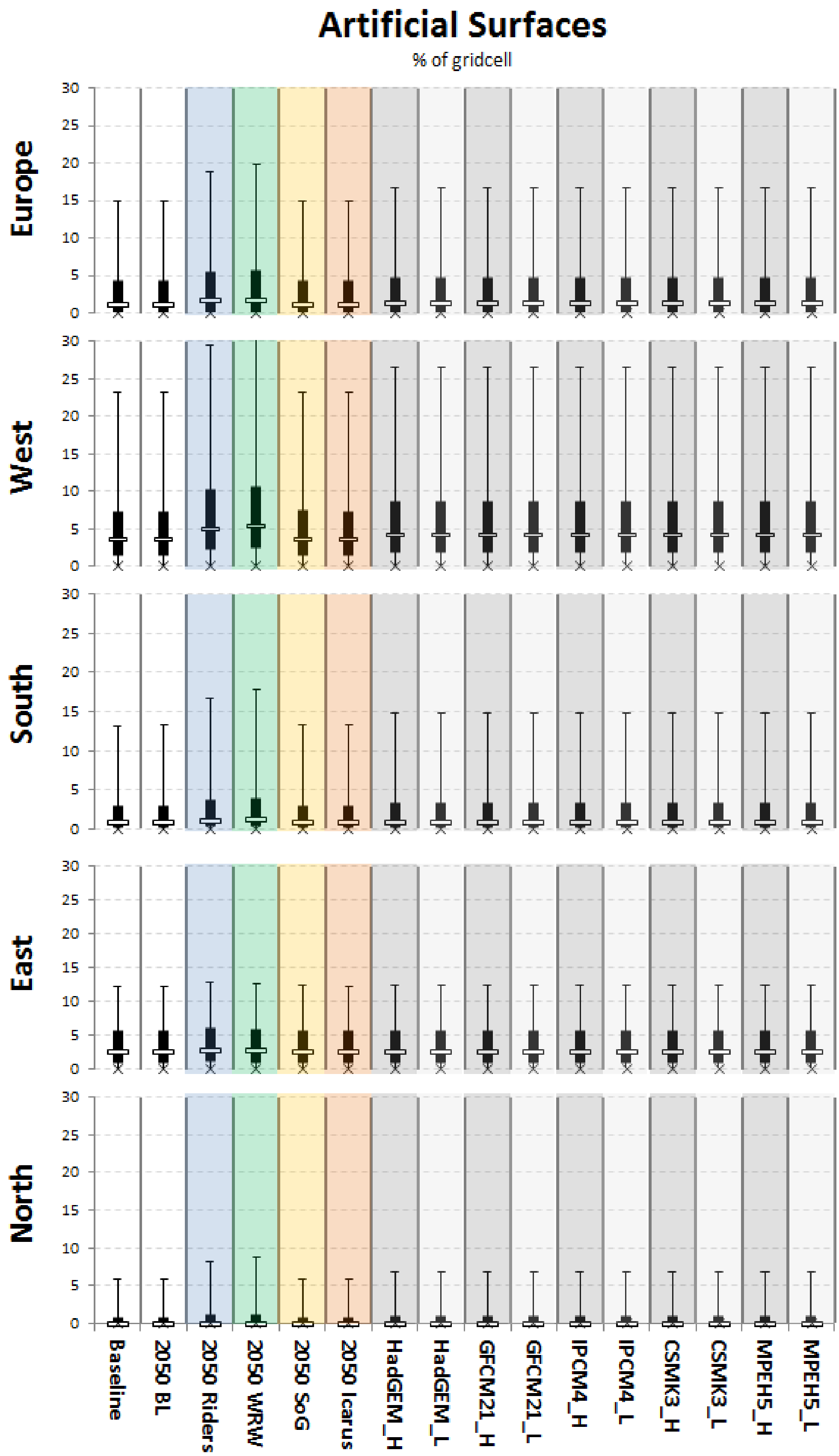
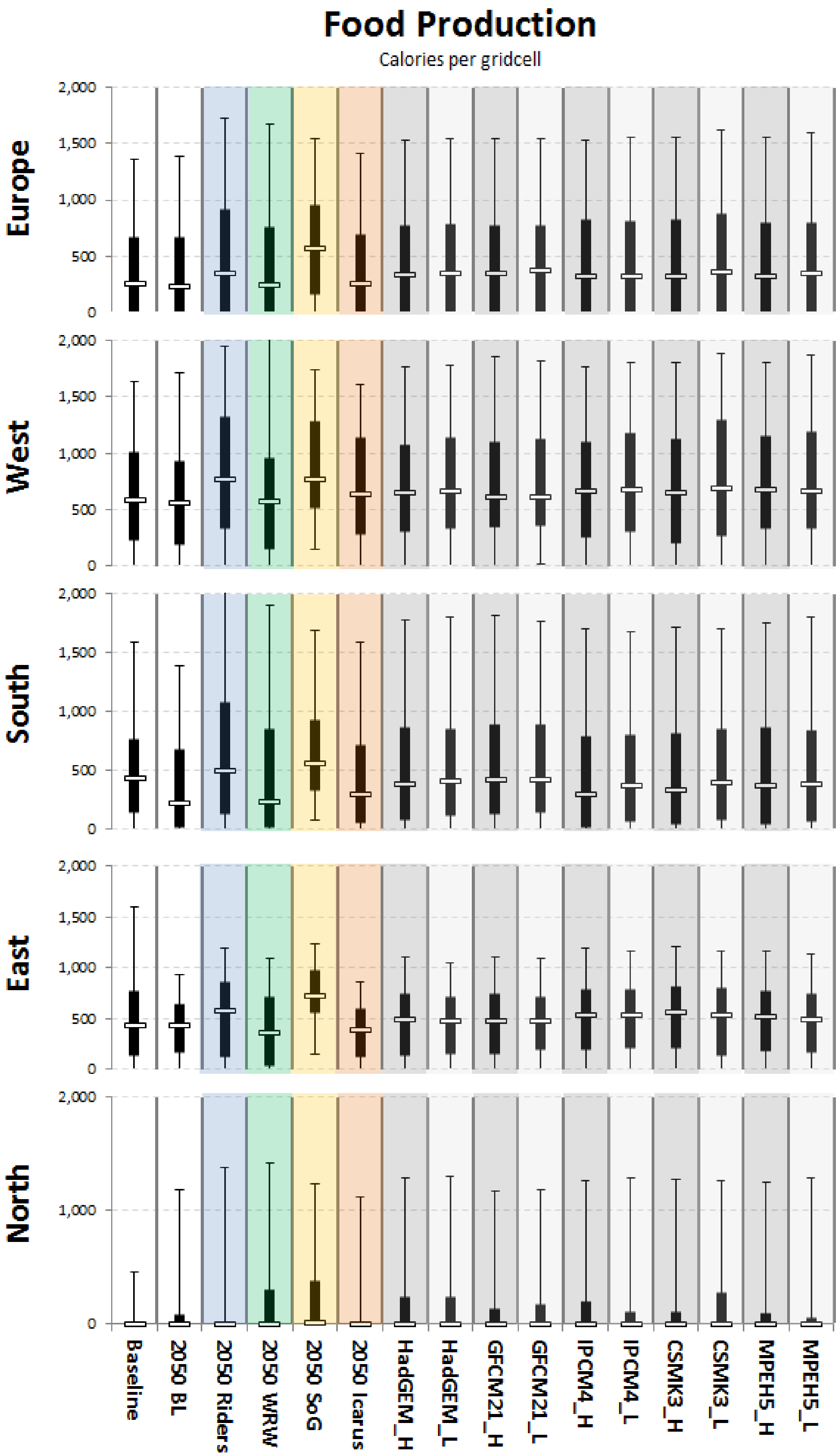
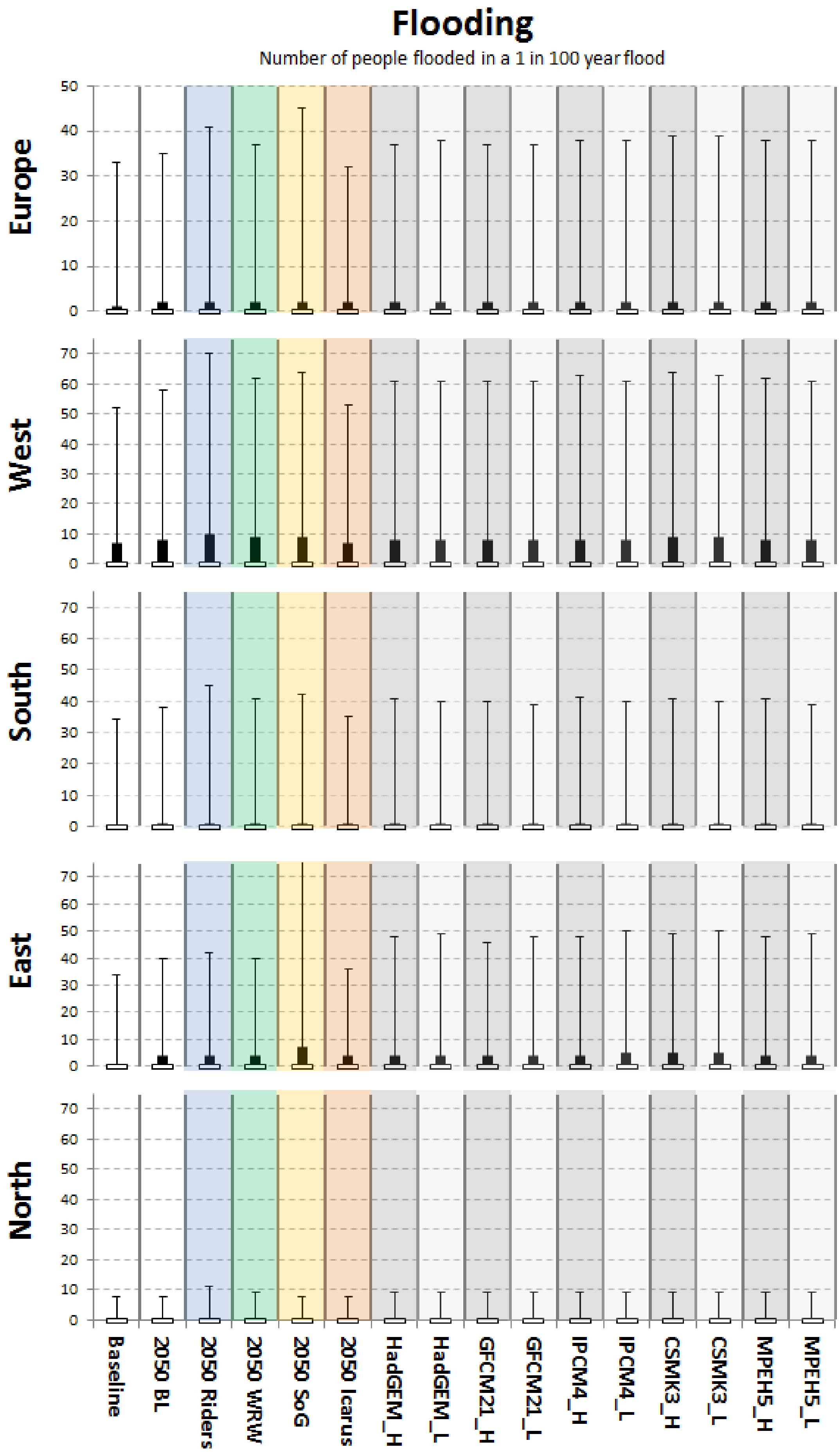
Appendix A

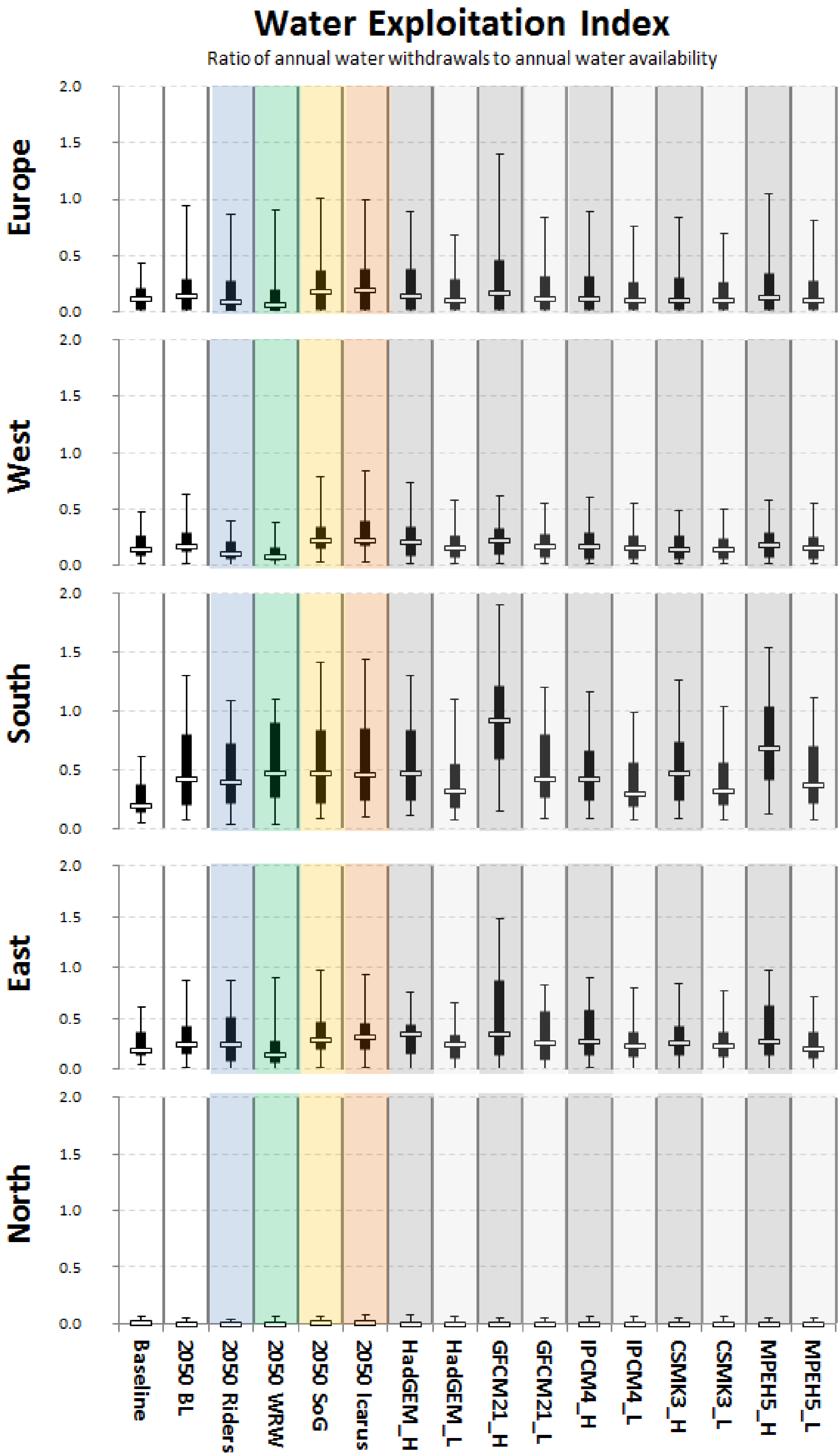


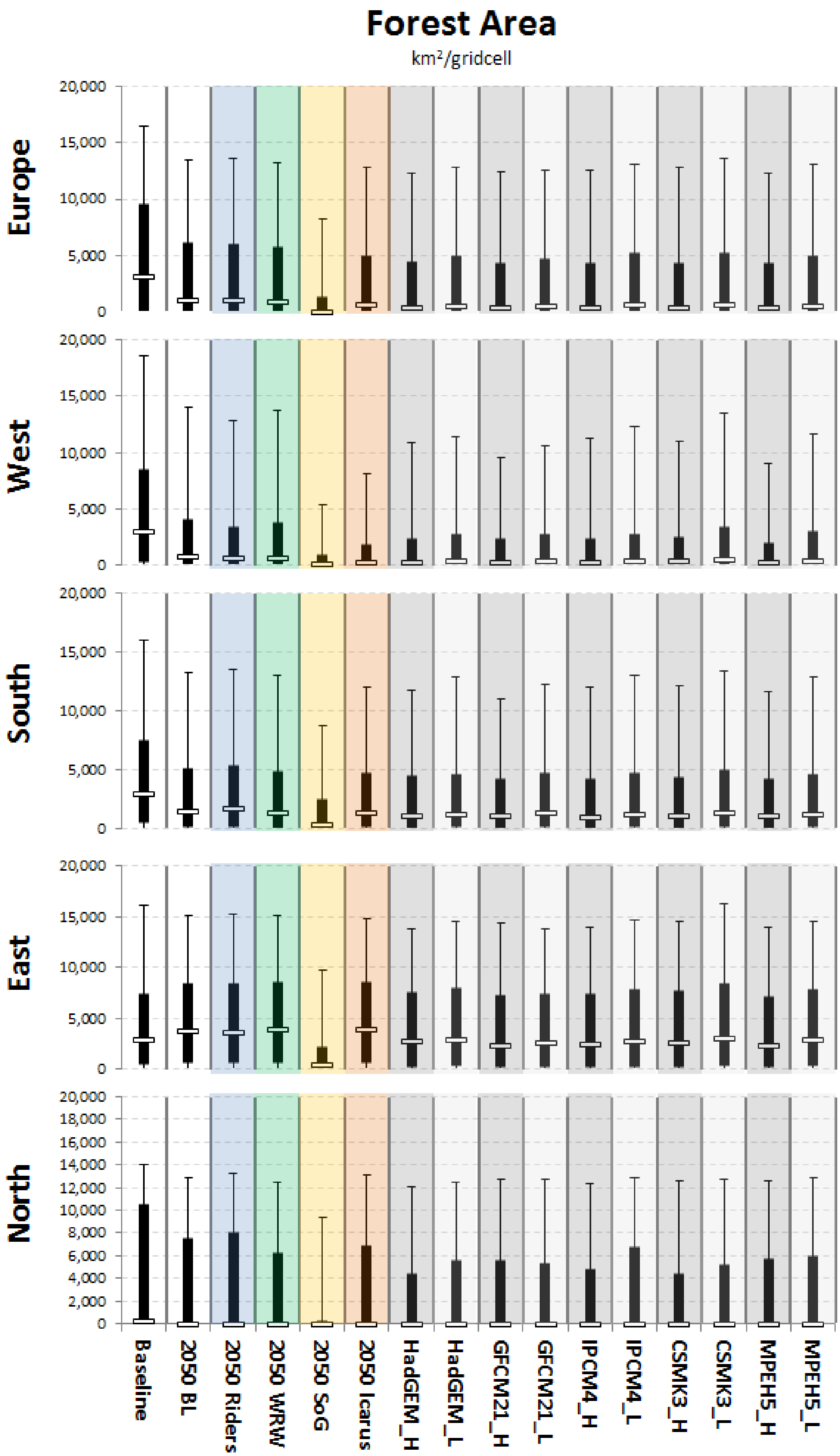
Artificial Surfaces
% of gridcell
Europe
West
South
East
North
30
25
20
15
10
5
0
Baseline
2050 BL
2050 Riders
2050 WRW
2050 SoG
2050 Icarus
HadGEM_H
HadGEM_L
GFCM21_H
GFCM21_L
IPCM4_H
IPCM4_L
CSMK3_H
CSMK3_L
MPEH5_H
MPEH5_L


Food Production
Calories per gridcell
Europe
West
South
East
North
0
500
1,000
1,500
2,000
Baseline
2050 BL
2050 Riders
2050 WRW
2050 SoG
2050 Icarus
HadGEM_H
HadGEM_L
GFCM21_H
GFCM21_L
IPCM4_H
IPCM4_L
CSMK3_H
CSMK3_L
MPEH5_H
MPEH5_L

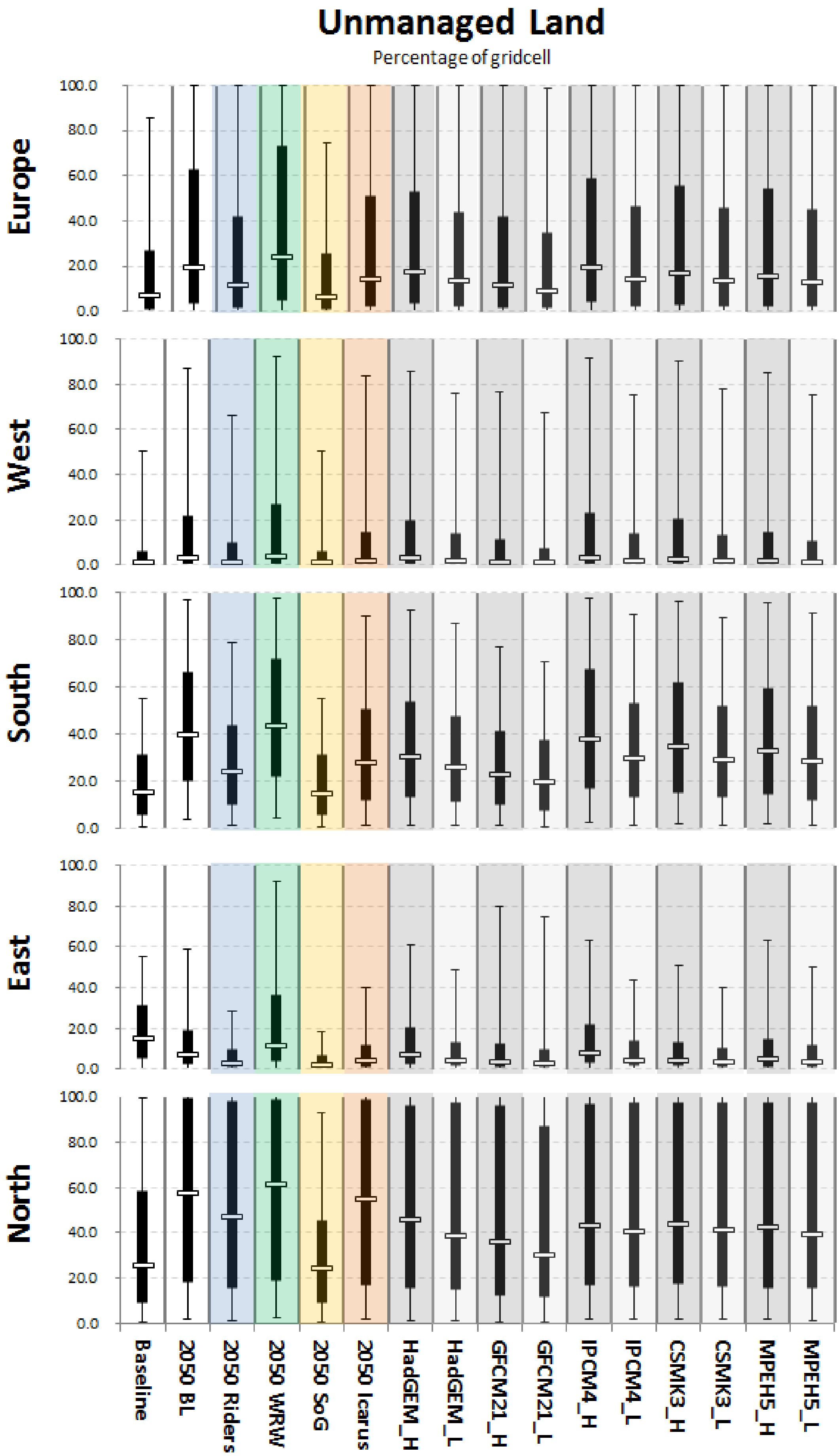


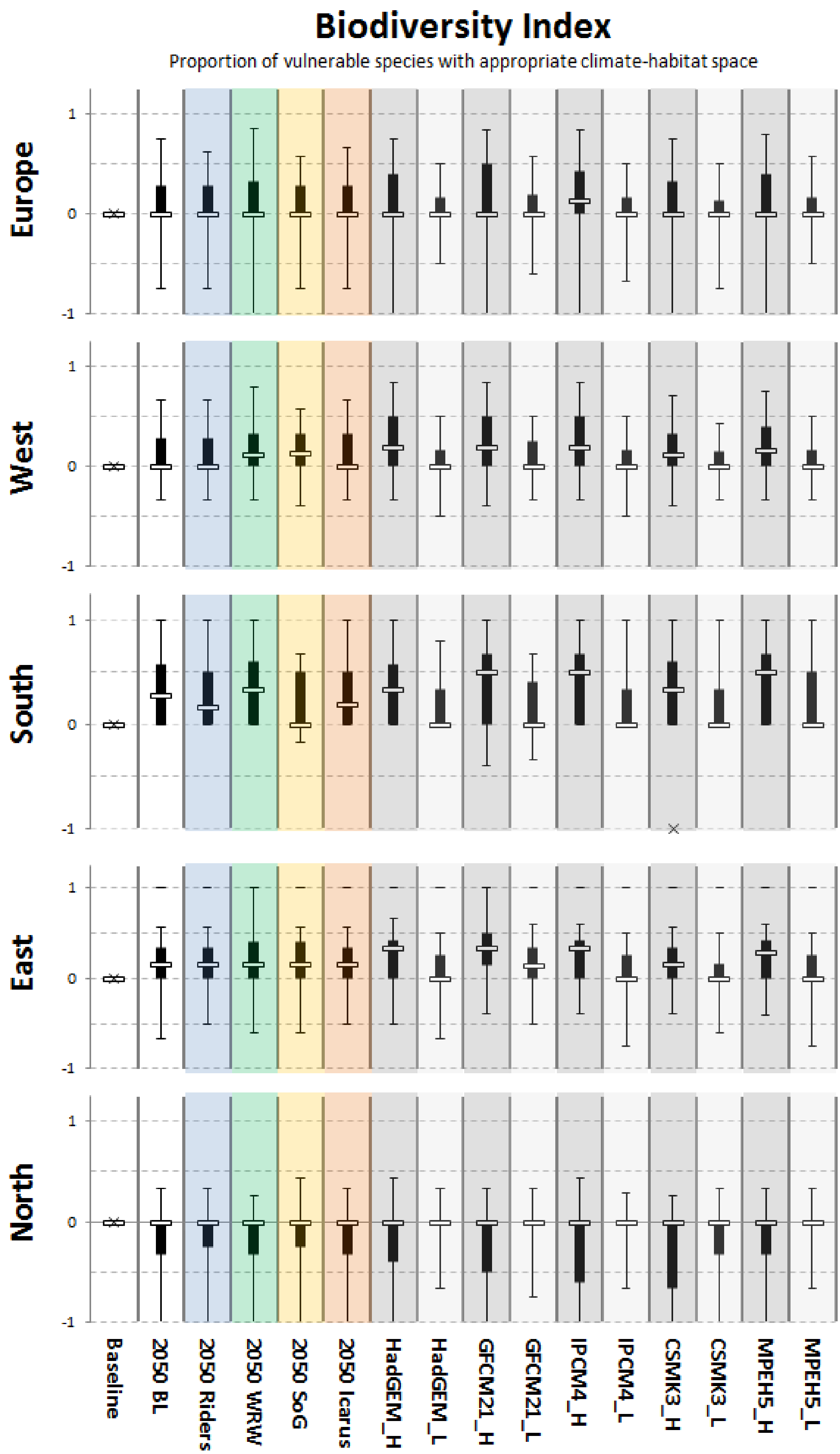
Flooding
Number of people flooded in a 1 in 100 year flood
Europe
West
South
East
North
Baseline
2050 BL
2050 Riders
2050 WRW
2050 SoG
2050 Icarus
HadGEM_H
HadGEM_L
GFCM21_H
GFCM21_L
IPCM4_H
IPCM4_L
CSMK3_H
CSMK3_L
MPEH5_H
MPEH5_L

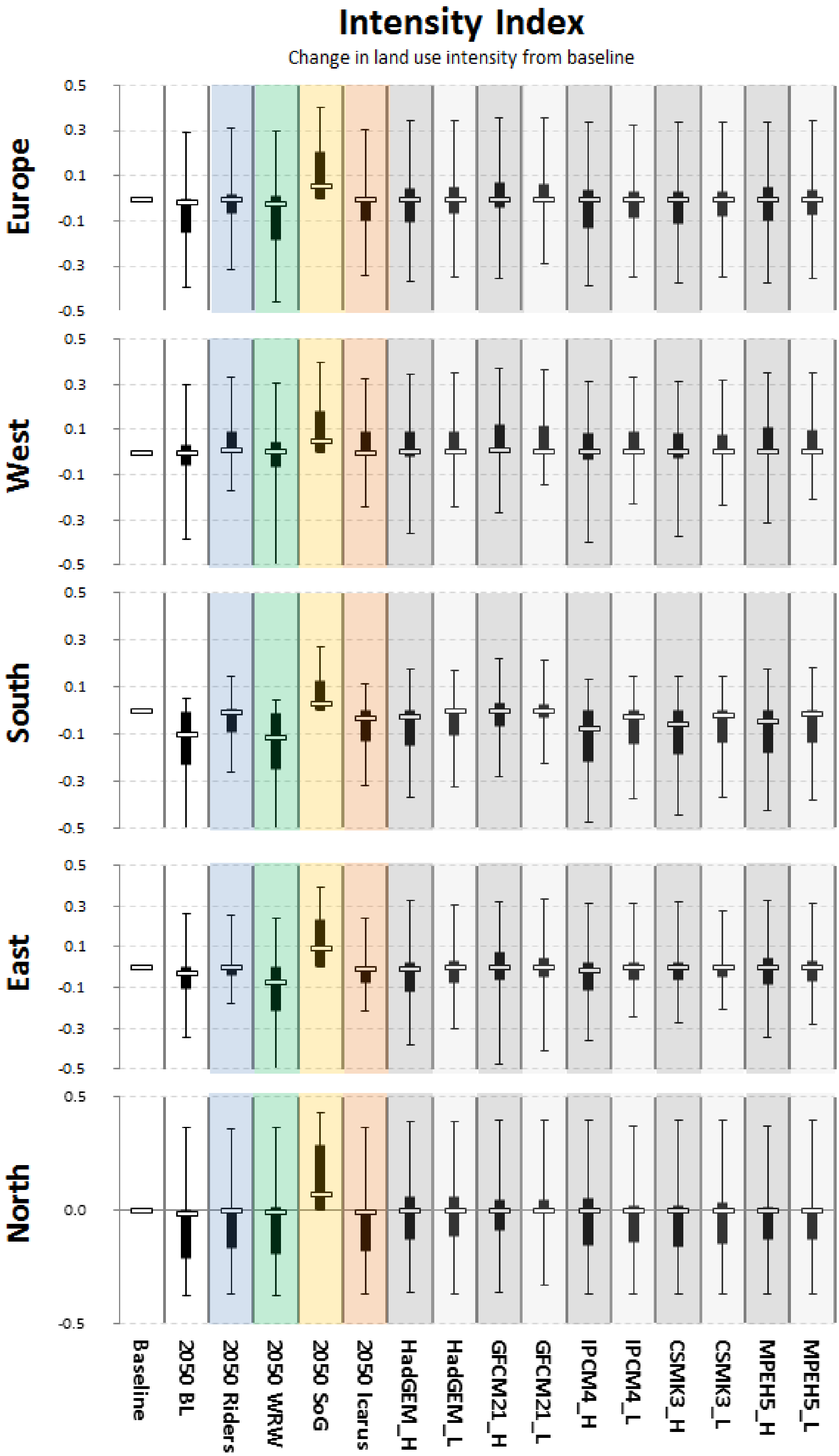

Water Exploitation Index
Ratio of annual water withdrawals to annual water availability
Europe
West
South
East
North
0.0
0.5
1.0
1.5
2.0
Baseline
2050 BL
2050 Riders
2050 WRW
2050 SoG
2050 Icarus
HadGEM_H
HadGEM_L
GFCM21_H
GFCM21_L
IPCM4_H
IPCM4_L
CSMK3_H
CSMK3_L
MPEH5_H
MPEH5_L



Forest Area
km²/gridcell
Europe
West
South
East
North
20,000
15,000
10,000
5,000
0
18,000
16,000
14,000
12,000
8,000
6,000
4,000
2,000
Baseline
2050 BL
2050 Riders
2050 WRW
2050 SoG
2050 Icarus
HadGEM_H
HadGEM_L
GFCM21_H
GFCM21_L
IPCM4_H
IPCM4_L
CSMK3_H
CSMK3_L
MPEH5_H
MPEH5_L


Unmanaged Land
Percentage of gridcell
Europe
West
South
East
North
100.0
80.0
60.0
40.0
20.0
0.0
Baseline
2050 BL
2050 Riders
2050 WRW
2050 SoG
2050 Icarus
HadGEM_H
HadGEM_L
GFCM21_H
GFCM21_L
IPCM4_H
IPCM4_L
CSMK3_H
CSMK3_L
MPEH5_H
MPEH5_L


Biodiversity Index
Proportion of vulnerable species with appropriate climate-habitat space
Europe
West
South
East
North
1
0
-1
Baseline
2050 BL
2050 Riders
2050 WRW
2050 SoG
2050 Icarus
HadGEM_H
HadGEM_L
GFCM21_H
GFCM21_L
IPCM4_H
IPCM4_L
CSMK3_H
CSMK3_L
MPEH5_H
MPEH5_L



Intensity Index
Change in land use intensity from baseline
Europe
West
South
East
North
0.5
0.3
0.1
-0.1
-0.3
-0.5
0.0
Baseline
2050 BL
2050 Riders
2050 WRW
2050 SoG
2050 Icarus
HadGEM_H
HadGEM_L
GFCM21_H
GFCM21_L
IPCM4_H
IPCM4_L
CSMK3_H
CSMK3_L
MPEH5_H
MPEH5_L