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Contact UKCEH NORA team at
noraceh@ceh.ac.uk

Integrated Assessment of the Food-Water-Land-Ecosystems Nexus in Europe: Implications for Sustainability

Abiy S. Kebede^{1,2*}, Robert J. Nicholls^{3,2}, Derek Clarke², Cristina Savin⁴, Paula A. Harrison^{5,6}

¹*Department of Civil and Environmental Engineering, Brunel University London, Uxbridge UB8 3PH, UK*

²*School of Engineering, University of Southampton, Southampton SO16 7QF, UK*

³*Tyndall Centre for Climate Change Research, University of East Anglia, Norwich NR4 7TJ, UK*

⁴*TIAMASG Foundation, Sfintii Voievozi 6, 010963 Bucharest, Romania*

⁵*Centre for Ecology & Hydrology, Lancaster Environment Centre, Lancaster LA1 4AP, UK*

⁶*Environmental Change Institute, University of Oxford, Oxford OX1 3QY, UK*

⁺ *Corresponding author – Email: Abiy.Kebede@brunel.ac.uk; Tel: +44 (0) 18 9526 8183*

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Abstract

Climate and socio-economic change impacts are likely to cross traditional sectoral and regional boundaries with cascading indirect, and potentially far-reaching, repercussions. This is particularly important for the food-water-land-ecosystems (FWLE) nexus, which is fundamental for the achievement of at least six of the seventeen Sustainable Development Goals (SDGs). A holistic understanding of the FWLE nexus interactions and how and to what extent various exogenous drivers of change affect them is therefore central to cross-sectoral adaptation planning. Here, we present such an integrated assessment for Europe applying a regional Integrated Assessment Platform (IAP). The study explores a wide range of future climate and socio-economic scenarios using more than 900 model simulations. The results show that food production is likely to be the main driver of Europe's future landscape change dynamics (with or without climate change). Agriculture and land use allocation is often driven by complex cross-sectoral interactions with cascading effects on other sectors such as forestry, biodiversity, and water under the various scenarios. The modelling also highlighted that while sustaining current levels of food production at the European level could be achievable under most climate and socio-economic scenarios, there are significant regional differences with winners and losers. The analysis raises the question of whether current production and consumption policies are sustainable in the long-term. Such systematic integrated model-based analysis plays a crucial role in informing development of cross-sectoral policies that maximise synergies and minimise trade-offs across nexus sectors, regions, and scenarios. This is essential to achieve the SDGs.

Key Words: *Food-water-land-ecosystems nexus; climate and socio-economic change; cross-sectoral impacts; integrated assessment; sustainability; Sustainable Development Goals (SDGs)*

1. Introduction

The world has strong aspirations to achieve the Sustainable Development Goals (SDGs) of the United Nations' 2030 Sustainable Development Agenda (e.g., Le Blanc 2015). However, the potential conflicts and trade-offs between the various nexus sectors that underpin the different SDGs are less explored (e.g., Allen *et al.* 2018; Nilsson *et al.* 2018). In Europe, the use of land- and water-based resources are increasingly constrained with challenges for maintaining production (e.g., agricultural and forest goods) to a point where their capacity to meet current and future consumption demands may be threatened (e.g., FAO 2011; Holman *et al.* 2017; Kluts *et al.* 2017; van Vliet *et al.* 2013). In addition, agricultural and other land use changes have important implications for biodiversity (e.g., effects of fertiliser and pesticides; Geiger *et al.* 2010; Henle *et al.* 2008; Rounsevell *et al.* 2006). These risks are further exacerbated by less-sustainable production practices (e.g., intensification and/or abandonment of farming), increasing socio-economic pressures, and climate change. Sustainable use and management of these resources and robust, long-term climate change adaptation policy decisions require a better understanding of the linkages and inter-dependencies between the various system components (e.g., Bleischwitz *et al.* 2018; Liu *et al.* 2018; Rasul 2016). This is particularly important for the food-water-land-ecosystems (FWLE) nexus, which is fundamental for at least six of the seventeen SDGs. These include: SDG2: Zero Hunger, e.g., *sustainable food production*; SDG6: Clean Water and Sanitation, e.g., *improving water-use efficiency*; SDG11: Sustainable Cities and Communities, e.g., *sustainable urbanisation*; SDG12: Responsible Consumption and Production, e.g., *sustainable use and management of natural resources*; SDG13: Climate Action, e.g., *impacts reduction and adaptation to climate change*; SDG15: Life on Land, e.g., *reducing loss of biodiversity*.

Analysis of sustainability issues is inherently multi-dimensional and interconnected across the three pillars of sustainable development: (i) social, (ii) economic, and (iii) environmental (Giddings *et al.* 2002; Lozana 2008). Important environmental (e.g., climate change) and socio-economic (e.g., technological, demographic) trends underlie these issues (e.g., UN 2013), trends that are expected to continue through this century and beyond (O'Neill *et al.* 2014; van Vuuren *et al.* 2011). There are also potential synergies

and conflicts within and between the SDGs, which are not widely discussed (e.g., Hutton *et al.* 2018; Yamagata *et al.* 2018). A holistic understanding of the FWLE nexus interactions and how these change under potential futures is, hence, key to identifying synergies and harmful trade-offs between food, water and land use systems, and, in turn, the long-term health and productive potential of ecosystems that provide important services and support biodiversity and livelihoods (e.g., Albrecht *et al.* 2018). This is crucial to informing development of cross-sectoral policies and achieving the SDGs in Europe and more widely.

Previous studies have assessed these issues either qualitatively or quantitatively using a limited number of scenarios and sectors, potentially ignoring important drivers and uncertainties, and the resulting complex cross-sectoral interactions (e.g., Schweizer and Kurniawan 2016). Ideally, quantitative assessment of sustainability issues should consider diverse plausible futures across scales within model-based “multidimensional exploratory scenarios” (e.g., Lord *et al.* 2016) and applied across the range of multiple sectors representing the nexus system (e.g., Harrison *et al.* 2015a,b, 2016; Jacob *et al.* 2018; Wachsmuth 2015). Systems integration and nexus-based approaches offer this ability (e.g., Bazilian *et al.* 2011; Liu *et al.* 2015, 2018). Such approaches allow identification of key co-benefits and potential conflicts between multiple sectors as well as endogenously simulating socio-environmental impacts under various drivers of change (e.g., Albrecht *et al.* 2018; Hoff 2011; Howells and Rogner 2014; Romero-Lankao *et al.* 2017; Stafford-Smith *et al.* 2017; UN 2015; 2017). They can also inform the development of robust, cross-sectoral policies under uncertain futures (e.g., Jäger *et al.* 2015; Reilly and Willenbockel 2010; Swart *et al.* 2004; van Vuuren *et al.* 2014). In this paper, we apply such a modelling framework, a regional integrated assessment platform (IAP) of Europe (Harrison *et al.* 2015a), to assess the complex FWLE nexus interactions and associated key implications for sustainability. The study explores more than 900 stylised scenarios of key climatic and socio-economic change driver combinations sampling a wide range of uncertainty.

2. Method and Materials

Quantitative assessment of multiple-sector interactions and associated impacts of multiple drivers of change requires application of integrated analytical approaches and models (e.g., Allen *et al.* 2018). Liu *et al.* (2018) suggested that a nexus-based modelling approach in principle should involve five key steps: (i) formulate nexus research goals, (ii) define system(s) of interest, (iii) develop conceptual framework, (iv) analyse relationships, and (v) simulate dynamics. This procedure involves key choices in terms of selecting representative impact metrics, identifying key drivers of change (both climatic and non-climatic), considering the wider uncertainty space and associated plausibility of future scenarios, and assessing key impacts across sectors, scales, and scenarios.

In this study, a regional integrated assessment model, the CLIMSAVE IAP¹, is applied to explore Europe-wide and regional area-averaged projections, as well as spatial variability, of future impacts across the FWLE nexus. The IAP is an interactive and freely available web-based platform that allows users to quantitatively assess climate change impacts, vulnerability and adaptation considering various climate and socio-economic scenarios. It integrates a number of meta-models (Holman and Harrison 2012) representing six key land- and water-based sectors, namely, agriculture (Audsley *et al.* 2015), biodiversity (Harrison *et al.* 2006), fluvial and coastal flooding (Mokrech *et al.* 2015), forestry (Morales *et al.* 2005), urban development (Reginster and Rounsevell 2006), and water resources (Wimmer *et al.* 2015). This study focuses on seven impact indicators (Table 1) that represent key nexus interactions and associated impacts across the six sectors.

Table 1: Selected nexus impact indicators.

	Indicators	Indicator Description	Brief Model and Data Description¹
1	Food production	Measure of food productivity of land based on total food (or feed) produced as crops or	A mechanistic farm-based optimizing linear programming of long-term strategic agricultural land use and soil/climate clustering approach is used to simulate food production. The modelling is based on the relative profitability of crops and trees and demand

¹ Refers to the Integrated Assessment Platform developed by the CLIMSAVE (CLimate change Integrated assessment Methodology for cross-Sectoral Adaptation and Vulnerability in Europe) project (www.climsave.eu; see Harrison *et al.* 2013, 2015a).

		livestock in terms of their metabolisable energy.	for food/feed to determine the most profitable land use (Audsley <i>et al.</i> 2015). The study focuses on twelve crop types: winter and spring wheat, winter and spring barley, winter oil seed rape, potatoes, grain maize, sunflower, soybean, cotton, grass, and olives. The soil input data is based on the European soil database ² – a total of 580 distinct soils are identified using a clustering procedure considering factors such as available water capacity and eliminating no soil (urban) or very shallow soil types (bare rock) based on CORINE database ³ . The climate input data (monthly precipitation, temperatures, evapotranspiration, radiation and wind) is based on Dubrovsky <i>et al.</i> (2015).
2	People flooded	Number of people flooded by a 1-in-100 year event due to both coastal and fluvial flooding	The number of people flooded is simulated by combining estimates of the areas at risk of flooding based on topography and relative sea-level rise and change in peak river flow and indicative level of protection of flood defences and population distribution within these areas (see Mokrech <i>et al.</i> 2015). Key datasets used include: land cover map (CORINE dataset), elevation data (ESRI SRTM data), population density and GDP (EUROSTAT NUTS data ⁴), extreme sea levels and land uplift/subsidence (DIVA database; Vafeidis <i>et al.</i> 2008), and simulated fluvial flood maps (based on Feyen <i>et al.</i> 2012).
3	Water exploitation index	Dimensionless ratio of annual water withdrawals for agricultural, domestic/industrial, environmental and cooling use to water availability from renewable resources	The water meta-model uses look-up tables to emulate the performance and reproduce the outputs of the original WaterGAP3 ⁵ (Water-Global Assessment and Prognosis) model on hydrology and water use (see Wimmer <i>et al.</i> 2015). The simulation takes into account simultaneous changes in temperature and precipitation to estimate water availability. The amount and relative changes in water use (withdrawal and consumption for the domestic, manufacturing and electricity sectors) are estimated considering country level factors such as population, GDP, production of thermal electricity, gross values added from manufacturing, and water efficiency measures due to behavioural and technological changes. The agriculture model simulates agricultural water use.
4	Artificial surfaces	Mean percentage changes in residential and non-residential areas	The change in the proportion of artificial surfaces is simulated as a function of changes in socio-economic variables (population, GDP per capita) and societal values (strictness of planning constraints to limit sprawl, household preferences for proximity to green spaces, social amenities, attractiveness of the coast in terms of scenic values or flood risk) (Reginster and Rounsevell 2006). The baseline estimates are based on the area of residential and non-residential properties from CORINE land cover data ³ .
5	Land use diversity	Representation of multi-functionality of the landscape based on Shannon Index, for land uses such as urban, intensive arable, intensive grass, extensive grass, forest and others	The Shannon Index metric is estimated based on outputs of the rural land use allocation and urban models with areas of the six land uses considered to represent the indicator (e.g., Dunford <i>et al.</i> 2015).
6	Biodiversity vulnerability index	Dimensionless metric representing changes in climate and habitat suitability for twelve ⁺ representative species covering a range of flora and fauna from different habitats and regions	The biodiversity meta-model is used to simulate the suitable climate space of a large number of species selected to interact with other sectors/sub-systems such as agriculture, forestry, coastal and water, and to indicate a range of associated ecosystem services. The simulation is based on ensembles of ANNs and incorporates bioclimatic variables, i.e., climate (temperature, precipitation, solar radiation and wind speed) and soil moisture (available water holding capacity), to characterise bioclimatic suitability envelopes for providing projections of species' distributions. Harrison <i>et al.</i> (2006) provides detailed description baseline data, including observed species' distributions (e.g., published literature for

			insects and mammals, European Bird Census Council for birds).
7	Timber production	Total timber produced based on the modelled timber productivity of five ^x representative European tree species within areas of modelled profitable managed forest	The impacts of climate change on forest ecosystem services (e.g., wood production, wood balance) and the benefits of forest management are simulated using the meta-model that emulates the performance of the original GOTILWA+ (Growth Of Trees Is Limited by WATER) model (see Morales <i>et al.</i> (2005); Sallaba <i>et al.</i> (2015) for detailed model and data descriptions).
<p>[*]These are: (1) Common poppy (<i>Papaver rhoeas</i>), (2) Linnet (<i>Carduelis cannabina</i>), (3) Bilberry (<i>Vaccinium myrtillus</i>), (4) Hornbeam (<i>Carpinus betulus</i>), (5) Norway spruce (<i>Picea abies</i>), (6) Brown bear (<i>Ursus arctos arctos</i>), (7) Western dappled white butterfly (<i>Euchloe crameri</i>), (8) Common saltmarsh grass (<i>Puccinellia maritima</i>), (9) Strawberry clover (<i>Trifolium fragiferum</i>), (10) Bell heather (<i>Erica cinerea</i>), (11) Red deer (<i>Cervus elaphas</i>), & (12) Capercaillie (<i>Tetrao urogallus</i>). The above list of species group is selected from the total of 111 species (included in the SPECIES model that has been trained and validated for all species) to represent a cross-section of species from different taxa, habitats, and regions in Europe.</p> <p>^xThese are: (1) <i>Pinus sylvestris</i>, (2) <i>Pinus halepensis</i>, (3) <i>Pinus pinaster</i>, (4) <i>Quercus ilex</i>, and (5) <i>Fagus sylvatica</i>.</p> <p>¹The full description of the indicators, meta-models and input data specifics can be found in Holman and Harrison (2012).</p> <p>²European Soil Data Centre (ESDAC): http://eusoiils.jrc.ec.europa.eu/data.html.</p> <p>³CORINE Land Cover Data (CLC): https://land.copernicus.eu/pan-european/corine-land-cover.</p> <p>⁴EUROSTAT Nomenclature of Territorial Units for Statistics (NUTS) data: http://epp.eurostat.ec.europa.eu/portal/page/portal/nuts_nomenclature/introduction.</p> <p>⁵WaterGAP is a widely used global freshwater model and data specifics are described in detail elsewhere (e.g., Alcamo <i>et al.</i> (2003); http://www.watergap.de).</p>			

Fig. 1 illustrates the methodology concept and framework applied in this study for understanding the key nexus interactions and their potential implications for sustainability under a range of climate and socio-economic drivers combined into different scenarios.

The study particularly focuses on stylised scenario combinations of eight key exogenous drivers, which include four climatic (*temperature, summer precipitation, winter precipitation, and CO₂ concentration*) and four socio-economic (*population, GDP, food imports, and agricultural yields*) factors. They are identified based on an extensive local sensitivity analysis of the IAP, via a One-Driver-at-a-Time (ODAT) approach, focusing on those drivers that have ‘strong’ and ‘non-linear’ effects on more than one sector at the European scale (Kebede *et al.* 2015). A total of 915 scenario combinations are identified, which are sampled from a larger set of (~1800, referred hereafter as the ‘full-range’) scenario combinations of the above eight key drivers. The full-range scenarios were used to define the overall uncertainty space for a global, multi-dimensional sensitivity analysis of the IAP conducted using a Multiple-Drivers-at-a-Time (MDAT) approach (Kebede 2016). The combined ODAT and MDAT approaches are used as a basis for a systematic screening of the key drivers of change and plausibility of their scenario combinations used to explore the key uncertainties in cross-sectoral impacts and their spatial variability across Europe (see Fig. 1). The full-range IAP simulation runs consisted of 1200 climate scenarios and 600 socio-economic scenarios. They represent driver combinations considering a varying (4–8) number of states (values) for each driver as summarised in Table 2.

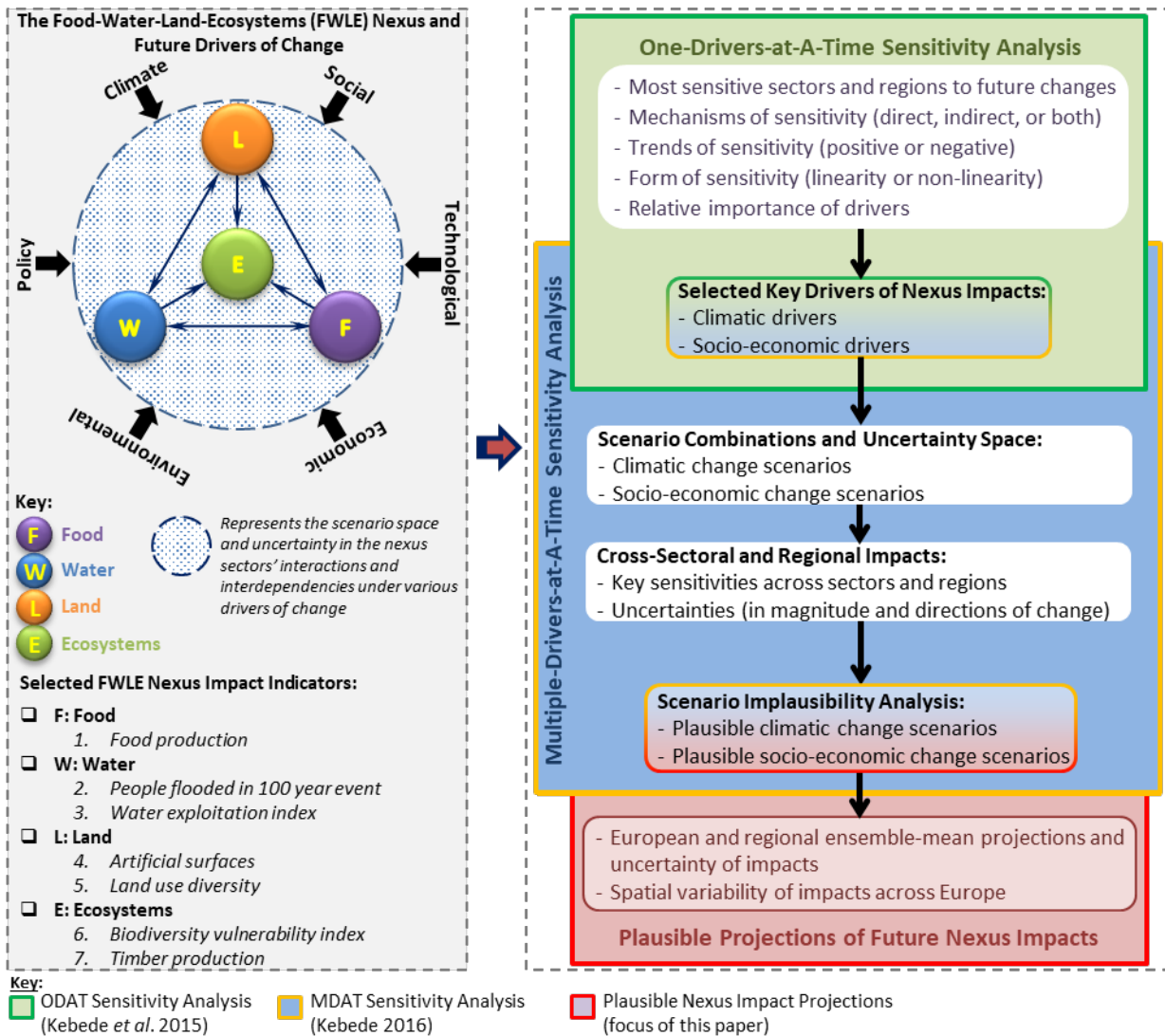


Figure 1: A methodological framework for integrated assessment of the food-water-land-ecosystems nexus in Europe using the CLIMSAVE IAP for sensitivity and scenario analysis.

Table 2: Selected values of the climate and socio-economic change drivers used in the full-range scenario simulations. Dubrovsky et al. (2015) and Kok et al. (2015) provide detailed descriptions of the selection process and data used in defining the value ranges for each climatic and socio-economic driver.

Change Driver	Minimum	Maximum	Interval
Climate Change			
Temperature change (°C)	0	5	1
Precipitation (Winter) (%)	-50	50	25
Precipitation (Summer) (%)	-50	50	25
CO ₂ concentration (ppm)	350	700	50
Socio-Economic Change			
Population (%)	-50	50	25
Gross Domestic Product (GDP) (%)	-20	200	-20%, then every 50% from 0
Food Imports (%)	-40	40	20
Agricultural Yields (%)	-50	100	50

The 'implausibility' analysis used in this paper for sampling a smaller set of credible scenarios from the full set is based on the approach developed and applied by Edwards *et al.* (2011). They used a sequential design experiment in order to assess the parameter-space of their model and identify 'low-dimensional regions that are implausible'. This is based on identifying key model pre-calibration outputs and 'physical' ranges by determining what is classed as 'non-physical' for their model. In this study, possible ranges of the selected impact indicators are identified based on a review of the literature on future projections of each indicator. The ranges are used to identify those MDAT scenarios that are considered as 'not-

implausible' and used for further analysis. In the absence of consistent data to define the 'physical' ranges of the seven diverse cross-sectoral impact indicators considered, the approach captures diverse 'expert opinions' and associated assumptions and methods employed in the literature. It also allows the key nexus impacts to be assessed using a consistent scenario and modelling approach within a single integrated framework. In addition, it helps identify spatial and regional variations within the Europe-wide projection ranges explored. Fig. 2 summarises the literature-based ranges of projections and their percentile distributions for each nexus impact metric. The broad range of estimates summarised also highlights the high uncertainties in future projections of changing conditions and their impacts in Europe.

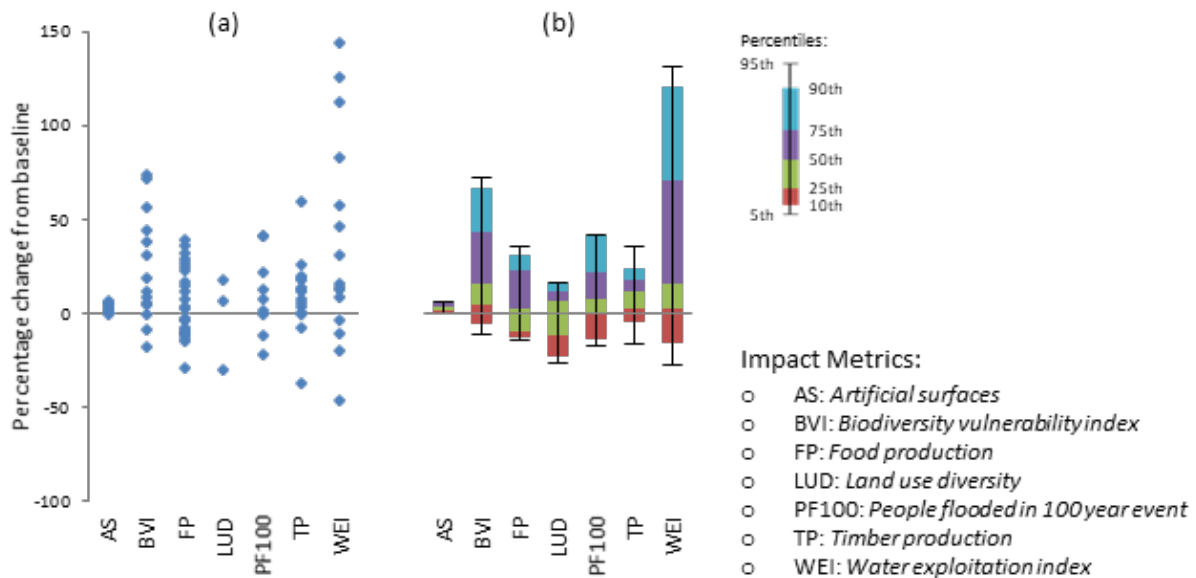


Figure 2: Summary of (a) the ranges and (b) percentile distributions of future projections of changes in the seven impact metrics (see ESM).

Considering the above ranges as boundary conditions, a total of 838 climate (70%) and 77 socio-economic (13% of the 'full range') scenarios are selected as plausible and applied in this study to estimate: (i) the ensemble-mean and uncertainty of the area-aggregated projections and (ii) the Europe-wide spatial distributions of nexus impacts across the scenarios. The first is modelled for Europe and its four sub-regions (eastern, northern, southern, and western Europe). The sub-regions are defined based on river basin classifications, chosen to have a consistent scale of analysis across all sectors (Kebede *et al.* 2015). The second is modelled based on a 10x10 arc-minutes grid resolution (i.e., ~16 km x 16km at the equator), which results in a total of 23,871 grid cells across Europe (covering the EU27, plus Norway, Switzerland, and United Kingdom). The results provide plausible and consistent (across sectors, regions, and scenarios) projections of future climate and socio-economic change impacts across Europe.

3. Results and Discussion

3.1 Baseline Estimates and Overview of Nexus Impacts across the Scenarios

The FWLE nexus synergies and trade-offs are represented by key interactions between the seven impact metrics explored under the various climate and socio-economic scenarios (Fig. 3).

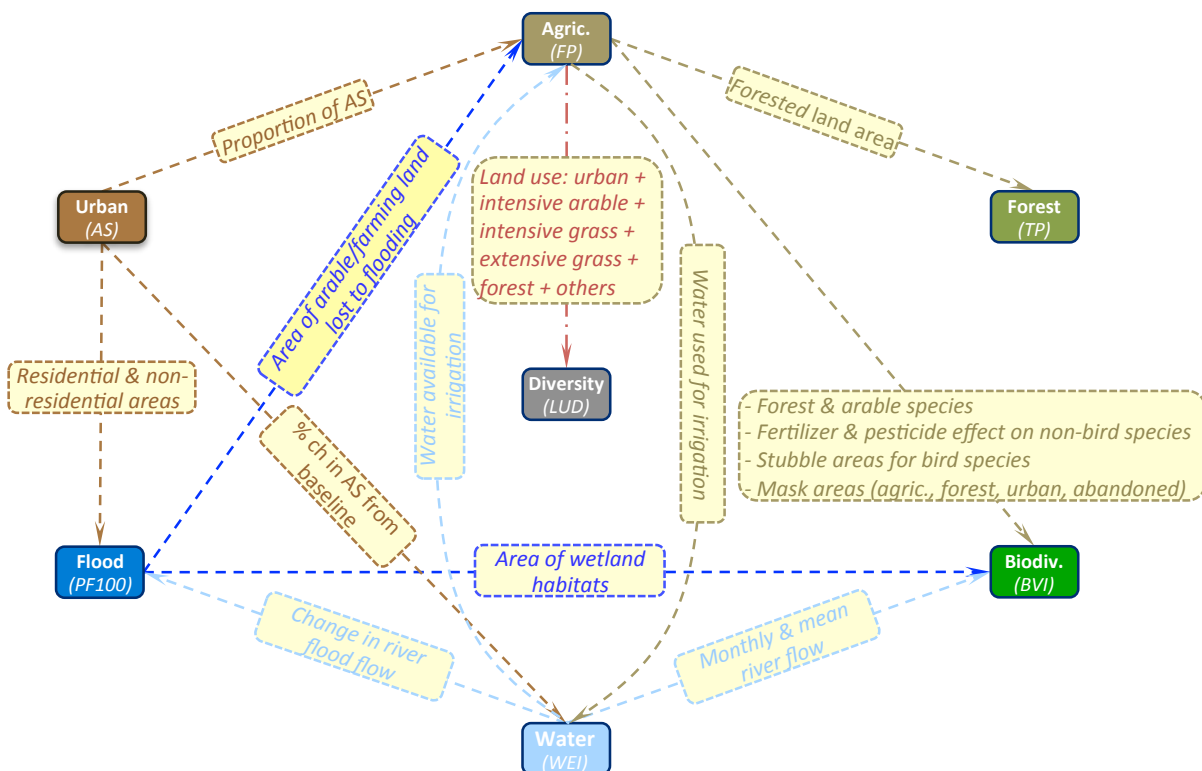


Figure 3: Simplified schematic diagram of the sectoral linkages and key interactions between the selected nexus impact metrics.

Table 3 summarises area-aggregated baseline estimates of the nexus impact metrics and study regions. The percentage change projections presented in the paper are relative to these estimates. The sources and year of baseline data used for each indicator are discussed in more detail in Holman & Harrison (2012).

Table 3: Area-aggregated baseline values of the seven nexus impact metrics.

Nexus Impact Metrics	Study Areas/Regions ⁺				
	WE	SE	EE	NE	EU
AS: Artificial surfaces (%)	6.5	3.0	4.1	1.2	3.7
BVI: Biodiversity vulnerability index (-)	0.0	0.0	0.0	0.0	0.0
FP: Food production (*1000 TJ)	4754	2473	2021	597	9845
LUD: Land use diversity (-)	0.51	0.59	0.58	0.33	0.48
PF100: People flooded in 100 year event (millions)	8.3	3.4	4.7	1.1	17.5
TP: Timber production (Gt)	106.5	35.6	47.4	72.8	262.3
WEI: Water exploitation index (-)	0.19	0.27	0.18	0.02	0.15

⁺ WE: Western Europe, SE: Southern Europe, EE: Eastern Europe, NE: Northern Europe, and EU: Europe

Fig. 4 shows statistical distribution of the nexus impacts under the various climate and socio-economic scenarios. For most indicators, changes under the socio-economic scenarios are relatively smaller than that of the climate scenarios across the study areas. However, there are significant variations in the distribution across the sectors, regions, and scenarios. At the European scale, most indicators increase in more than 50% of the climate scenarios, except for food production (only 10%), land use diversity (just 1%), and artificial surfaces (no change). Both the water stress and biodiversity vulnerability indices show the highest increase (by more than 47% and 17%, respectively) in at least a quarter of the climate scenarios.

In contrast, almost all indicators show a Europe-wide increase in at least 40% of the socio-economic scenarios. The two exceptions are land use diversity and timber production, which decline in almost all the scenarios. The water, agriculture, and flood impact indicators experience the highest increase (61%, 24%, and 24%, respectively) in a quarter of the socio-economic scenarios.

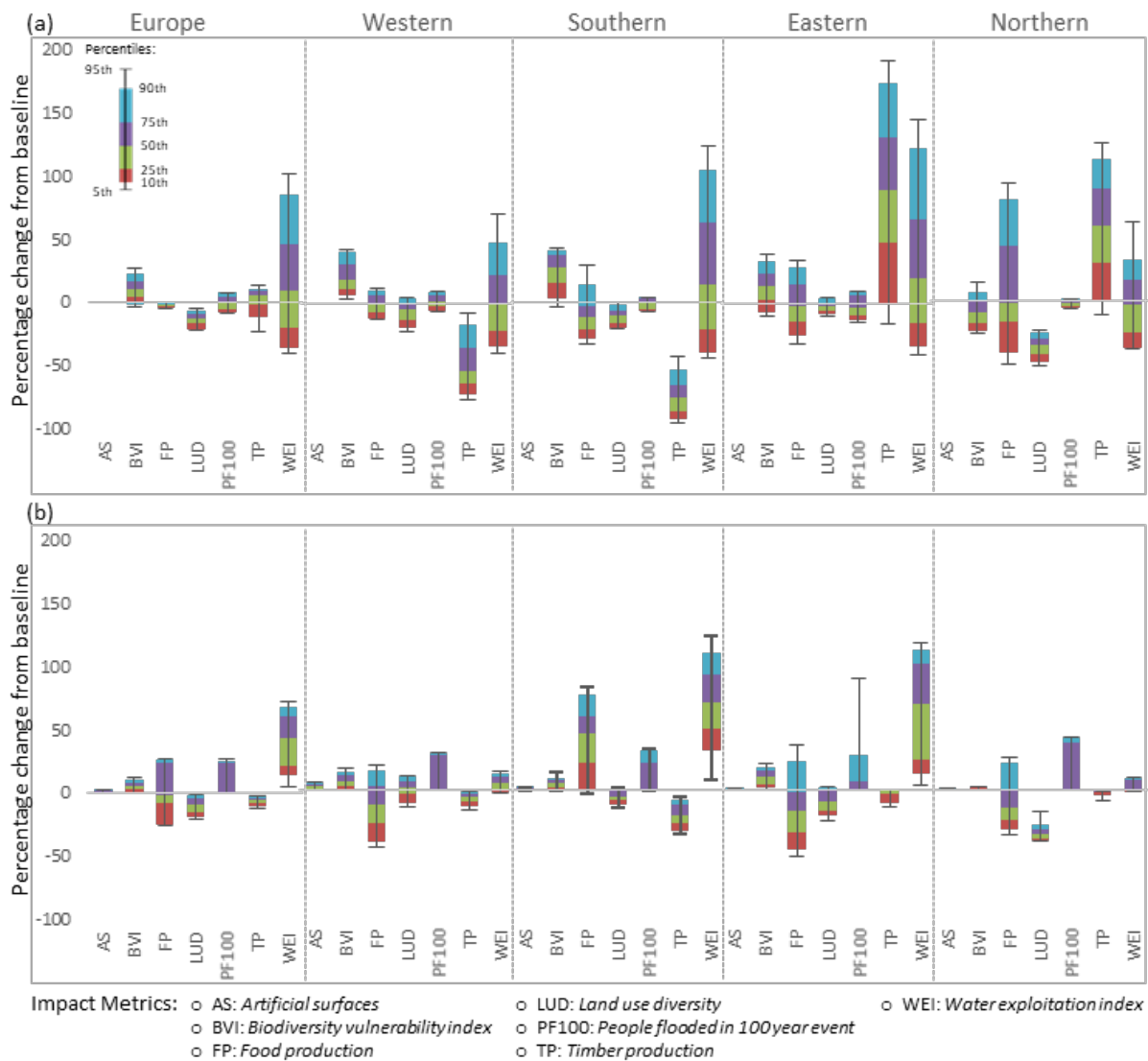


Figure 4: Percentile distribution of the % change (from baseline) in the nexus impact metrics under the: (a) 838 climate scenarios and (b) 77 socio-economic scenarios investigated.

The regional change patterns due to climate change vary across the sectors. The biodiversity, water, flooding, and agriculture indicators increase in more than 41% of the scenarios on average across the four regions. Notable exceptions are biodiversity (northern) and agriculture (southern Europe), which decline in over 75% of the scenarios. There are regional variations for forestry and land use diversity. Timber production declines in western and southern Europe in nearly all (over 97%) the climate scenarios, while more than 90% of the scenarios lead to an increase in eastern and northern Europe. Similarly, land use diversity increases in western and eastern Europe in 30% of the scenarios, while declining in southern and northern Europe in 94% the scenarios. The highest changes (across all scenarios and regions) are observed for timber production, over +59% in eastern and northern Europe and -54% in other regions in half of the climate scenarios.

Under the socio-economic scenarios, water, biodiversity and urban sectors increase across all four regions in more than 73% of the scenarios. Albeit small in proportion in other regions, food production in southern Europe also increases in more than 90% of the scenarios. In contrast, other sectors decline across all regions under most of the socio-economic scenarios. The highest increases are estimated for water stress (68% in southern and eastern Europe) and agriculture (45% in southern Europe).

3.2 Uncertainty of European and Regional Impacts

3.2.1 Due to Climate Change

The analysis is based on four key climatic factors (temperature, summer and winter precipitation, and CO₂ concentration) combined into more than 800 scenarios sampling a wide range of uncertainty. The Europe-wide projections show that there is high uncertainty in the direction of change in all indicators across the scenarios. The scenario-specific extreme estimates range between: -46 and +140% (water), -35 and +25% (forest), -13 and +37% (biodiversity), -12 and +19% (agriculture), -26 and +4% (land use diversity), and -11 and +8% (flooding). The highest ensemble-mean change is observed for Europe-wide water stress, which increases by 17% (Fig. 5). This is partly due to a decline in water availability and/or increase in irrigation need across the scenarios. This is followed by an overall decline in land use diversity (-13%) and an increase in biodiversity vulnerability (+11%). In contrast, forest, agriculture and flooding show the least (<3%) ensemble-mean change across the scenarios.

When looking at the mean±SD simulations, there is high uncertainty in the direction of change for water, forest and flooding. Other indicators, in contrast, show robust change across the scenarios, with an increase in biodiversity vulnerability and a decline in land use diversity and food production. In terms of magnitude, water stress shows the highest uncertainty (-27% to +62%). The large increase is mainly attributed to the extreme scenarios with high temperature increases and large declines in precipitation, affecting both the supply and demand side (Kovats *et al.* 2014). There is moderate uncertainty for timber production (-8% to +13%) and biodiversity vulnerability (2–20%). Other indicators show a relatively small uncertainty (SD<6%); with food production having the least variation (<2%). The latter is mainly due to the implicit adaptation within the IAP to meet Europe-level demand, with important spatial and regional implications as elaborated below.

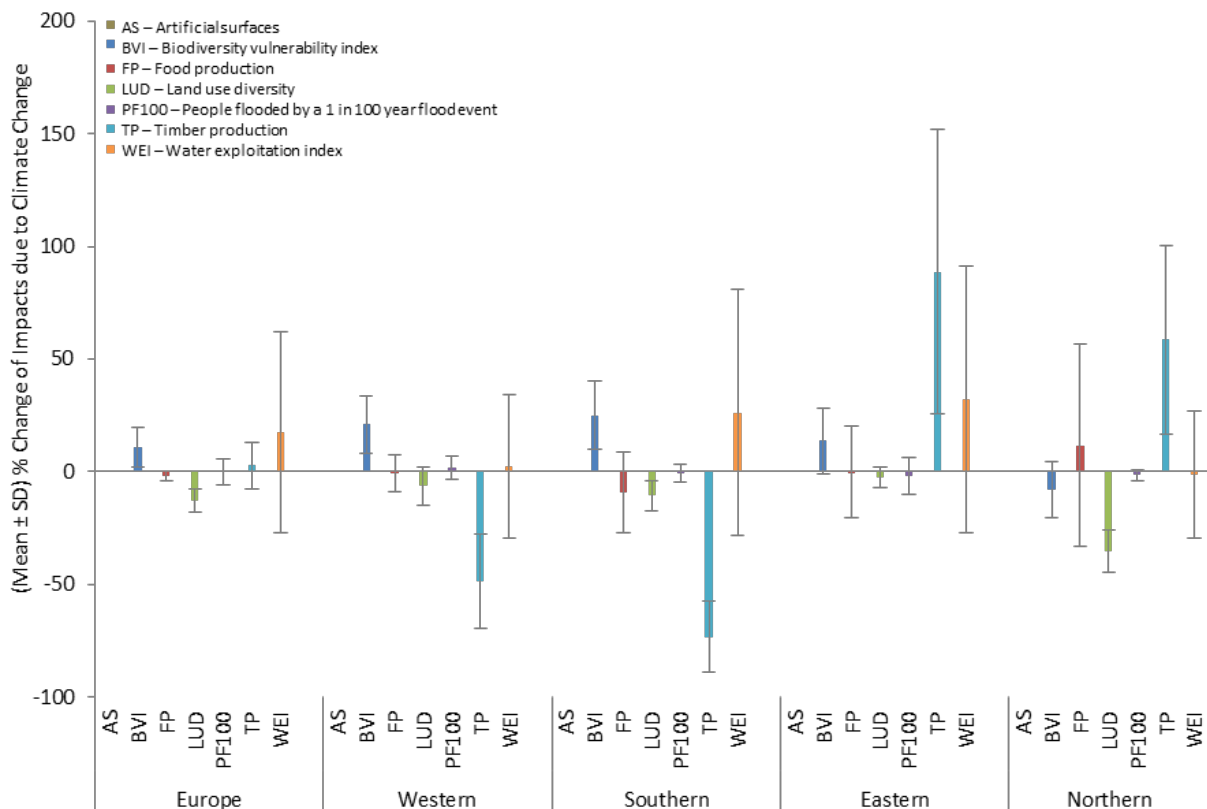


Figure 5: European and regional uncertainty of nexus impacts due to climate change based on (mean±SD) percentage change of the indicators from baseline. Coloured boxes represent the ensemble-mean across the scenarios, while error bars represent the SD from the mean.

There are notable regional variations both in terms of magnitude and direction of change. Under the ensemble-mean simulations, land use diversity declines across all four regions, by ~35% in northern Europe. For other indicators, there are regional variations in the direction of change. In terms of magnitude, timber production and water stress show the highest changes, with varying levels and directions across the regions. Timber production declines by up to 73% in southern and western Europe; while increasing by more than 59% in eastern and northern Europe. Similarly, the largest increase in

water stress is in southern (26%) and eastern (32%) Europe, while change is minimal in northern Europe. Biodiversity vulnerability is also projected to increase by 14%–25% across three regions, while northern Europe see some improvement (by 8%). The ensemble-mean changes in flood impacts are relatively small (<2%) across all four regions.

The ensemble-mean simulations also demonstrate that food production declines across three regions, by up to 9% in southern Europe. This is, however, compensated by a 12% increase in production in northern Europe, resulting in overall Europe-wide production being maintained at or close to baseline levels. This is driven by the autonomous adaptation within the land use allocation module in prioritising food production to meet Europe-wide demand (Audsley *et al.* 2015). The model determines the most optimal locations in Europe for crops and/or livestock when trying to meet food demand. This results in changing spatial patterns for agriculture for different scenarios with knock-on effects for forestry (competition for land), water (irrigation needs) and biodiversity (habitat availability) and changes in land use diversity. Veerkamp *et al.* (2020) also demonstrated similar Europe-wide observations even under the most optimistic scenarios. On the other hand, the declines in both land use diversity and biodiversity vulnerability in northern Europe reflect the northward shift of agriculture under extreme climate scenarios, dominating the land use (hence reducing diversity) and increasing habitat space (especially for arable-related species, hence reducing vulnerability).

Focusing on the mean \pm SD estimates, there are robust directions of change in some of the indicator-region combinations across the climate scenarios. These include: a decline in timber production (western and southern) and land use diversity (southern and northern Europe) and increasing timber production (eastern and northern) and biodiversity vulnerability (western and southern Europe). There is, however, uncertainty in the direction of change in the remaining indicator-region combinations (Fig. 5). In terms of magnitude, timber production shows the largest uncertainty: increasing by 25–152% (eastern) and 17–101% (northern) and declining in western (25–70%) and southern Europe (58–89%). Water stress follows with changes ranging between -29% and +92% across all four regions. For agriculture, the largest uncertainty is observed in northern Europe (i.e., -33% to +57%), followed by eastern and southern Europe (-27% to +20%). In contrast, biodiversity vulnerability shows relatively moderate uncertainty, with a standard deviation of just 14% averaged across the four regions. The larger uncertainty is estimated between +10% and +40% (southern) and -1% and 28% (eastern Europe). Land use diversity and flooding generally show the least variation around the ensemble-mean, with SD<7% across the regions and scenarios.

3.2.2 Due to Socio-Economic Change

The analysis explored more than 75 scenario combinations of four key socio-economic factors (i.e., population, GDP, food imports, and agricultural yields). The Europe-wide scenario-specific extreme projections range between: -1% and +79% (water), -26% and +29% (agriculture), -25% and -1% (land use diversity), -17% and 0% (forestry), +1 and +14% (biodiversity), +24 and +27% (flooding), and 0 and +3% (urban). This illustrates that there is more robustness in the extreme changes in most sectors under the socio-economic scenarios than the climate scenarios (see Section 3.2.1). For the ensemble-mean simulations, water stress shows the largest increase (42%, Fig. 6). Similarly, the number of people flooded and biodiversity vulnerability increase by 10% and 6%, respectively. In contrast, land use diversity and timber production are projected to decline by 10% and 6%, respectively. Food production shows the least change (just +1%), again due to the autonomous adaptation considered in the IAP.

When considering the mean \pm SD simulations, there is robustness in the direction of change for most sectors, except agriculture and flooding. The water, biodiversity and urban sectors show an increase, while land use diversity and forestry decline. In terms of magnitude, water stress (20–63%) and food production (-26% and +29%) show the largest uncertainty across the scenarios. This is followed by people flooded (-3% and +22%) and land use diversity (-16% and -4%). Biodiversity, forest, and urban indicators show the least variation around the mean (with SD<5%), ranging between 2–9%, -9 to -3%, and 0–3%, respectively.

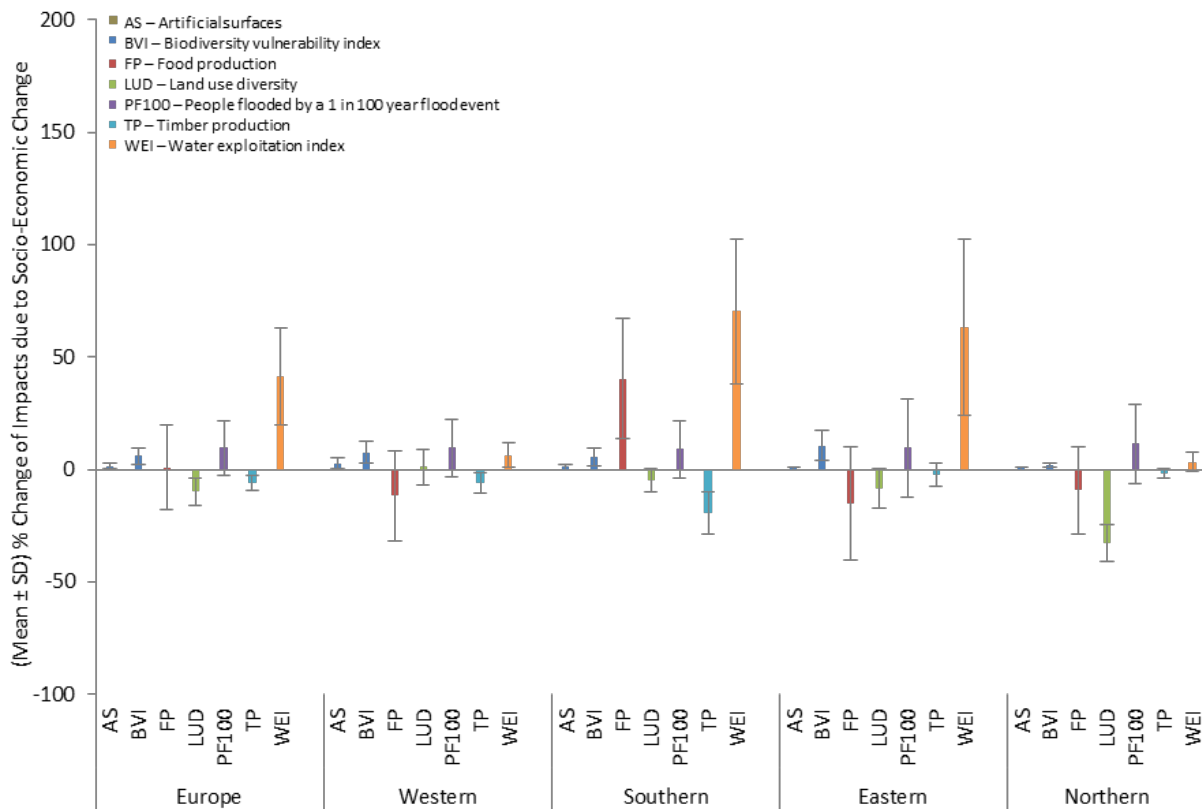


Figure 6: European and regional uncertainty of nexus impacts due to socio-economic change based on (mean±SD) percentage change of the indicators from baseline. Coloured boxes represent the ensemble-mean across the scenarios, while error bars represent the SD from the mean.

As in the climate scenarios, there are important regional variations (both in direction and magnitude of changes) under the socio-economic scenarios (Fig. 6). For the ensemble-mean simulations, most indicators are projected to get worse across all four regions, with only a few exceptions. In terms of magnitude, water stress is projected to increase by more than 63% in southern and eastern Europe, while there is a relatively small (<6%) change in western and northern Europe. Food production follows with a 40% increase in southern Europe. However, it is expected to decline by up to 15% across the other three regions. Except in western Europe (where it is expected to improve by just 1%), land use diversity is also projected to decline by up to 33% in northern Europe. Similarly, timber production is projected to decline across all four regions, with the largest in northern Europe (19%) and by 2–6% in other regions. Although relatively smaller in magnitude, there is also a consistent increase in the number of people flooded (9–12%) and biodiversity vulnerability (2–11%) across all regions. Artificial surfaces show the least change, with <3% increase across all four regions.

When comparing uncertainties based on the mean±SD simulations, there is robustness in the direction of change in most indicator-region combinations (with varying degrees of magnitude). Similar to the climate scenarios, timber production (western and southern) and land use diversity (northern Europe) are projected to decline across the socio-economic scenarios. In contrast, water stress (in all except northern Europe), food production (southern), biodiversity vulnerability and urbanisation (all regions) are all projected to increase. However, there is uncertainty in the direction of change in other indicator-region combinations, including flooding in all regions. In terms of magnitude, again water stress shows the largest change in eastern and southern Europe (24–103%, Fig. 6). In other regions, the ranges are relatively small (with SD<5%). In contrast, food production is projected to increase by 14–67% in southern Europe, while in other regions it is projected to both increase and decrease (between -40% and +10%) across the scenarios. The number of people flooded is also projected between -12% and 32% (the largest change in eastern Europe). Other indicators show relatively small to moderate variation, with SD<10% across all regions and scenarios. In comparison, timber production and land use diversity show a relatively larger uncertainty range, particularly in southern (timber by up to -29%) and eastern (diversity by up to -17%) Europe. Other indicator-region combinations with comparable variations also include land

use diversity in northern (-41 to -25%) and western (-7 to 9%) and biodiversity vulnerability in eastern (4–17%) Europe. Urban change shows the least variation (SD<3%) across all regions and scenarios.

3.2.3 Comparison of Impacts due to Climate and Socio-Economic Change

Table 4 summarises a comparison of implications of the climate and socio-economic scenarios to highlight the degree and main sources of uncertainty for each nexus indicator. This is based on ranking of the standard deviation (relative to the ensemble-mean) and sensitivity range (difference between the extreme minimum and maximum projections) across the scenarios.

Table 4: Comparing the standard deviation (left) and sensitivity range (right) of the Europe-wide and regional percentage changes of the indicators across the scenarios. The red and blue texts and shading represent the climate (CD) and socio-economic (SED) scenarios, respectively. Table 3 defines the code names used here for the indicators and regions.

Highest Standard Deviation		Regions					
		EU	WE	SE	EE	NE	
Nexus Impact Metrics	AS	1.2	2.5	1.1	0.4	0.6	
	BVI	8.9	12.6	15.1	14.6	12.3	
	FP	19.0	20.0	26.8	25.3	44.9	
	LUD	6.2	8.5	6.5	8.8	9.5	
	PF100	12.0	13.0	12.8	22.0	17.7	
	TP	10.6	21.1	15.9	63.4	42.1	
	WEI	44.6	31.8	54.7	59.3	28.0	
			Low	CD	High	Low	SED

Highest Sensitivity Range		Regions					
		EU	WE	SE	EE	NE	
Nexus Impact Metrics	AS	3	7	3	1	1	
	BVI	50	57	79	78	70	
	FP	55	70	112	100	256	
	LUD	30	38	36	31	67	
	PF100	20	23	30	81	27	
	TP	59	112	97	332	258	
	WEI	187	135	246	291	115	
			Low	CD	High	Low	SED

At the European scale, socio-economic factors dominate the largest sensitivity in food production and urbanisation, while other sectors' sensitivity is driven by climatic factors. Regionally, in almost all cases, either climate or socio-economic factors dominate the potential uncertainty of individual nexus impacts across all regions, with a few exceptions (see Table 4). Exceptions include food production in northern and southern Europe (depending on which metric considered) and land use diversity in eastern Europe. The largest uncertainty in most impact indicators is mainly due to the uncertainty in climate change. This is particularly true for timber production in eastern and northern Europe and water stress across most regions. While socio-economic factors play an important role in other regions, climate change is projected to drive the potential shift in agriculture towards northern Europe as warmer climate makes the region more productive. Climate change will also have important implications for biodiversity across all regions. In contrast, uncertainty in changes in regional flood impacts and urbanisation is mainly driven by socio-economic factors. These results highlight the importance of understanding the full uncertainties due to both climate and socio-economic change impacts across the nexus sectors. The following two sections discuss the grid-based spatial variation of these changes in more detail.

3.3 Spatial Distribution of Nexus Impacts across Europe

The area-aggregated results presented by region in previous sections average out sub-regional spatial variations of future changes in nexus impacts. This section presents the spatial distribution of each indicator based on the grid-based ensemble-mean simulations across the various climate and socio-economic scenarios.

3.3.1 Climate Change Scenarios

Fig. 7 displays spatial distribution of the potential hotspots of significant ensemble-mean changes (>50% from baseline) in nexus impacts across the climate scenarios. Biodiversity vulnerability and water stress show moderate (>5%) increase in almost 60% of the grids across Europe, resulting in a Europe-wide average increase of about 11% and 17%, respectively. Water stress hotspot areas due to climate change are identified in parts of Spain and Portugal, southern Italy, Romania, Bulgaria and Poland, covering ~13% of European grids. Similarly, southern France and Italy, some alpine areas in continental Europe and Denmark are potential hotspots for biodiversity vulnerability. This is partly due to the decline in arable habitats and climate suitability for some species under some of the scenarios. In contrast, parts of northern Europe (particularly southern Finland and alpine areas in Scandinavia), western Romania and Ireland are projected with a significant improvement in biodiversity. This is mainly associated with a northward shift in habitat distribution under warmer climate scenarios. The biodiversity module assumes that species will be able to disperse to occupy new climate and habitat space, so it may overestimate

biodiversity suitability in the north. Similarly, while the Europe-wide number of people affected by coastal and fluvial floods is relatively unchanged, there are important local implications. These areas represent about 6% of European grids, with hotspot areas particularly concentrated in western Europe (e.g., northern Germany), mainly due to a significant increase in precipitation.

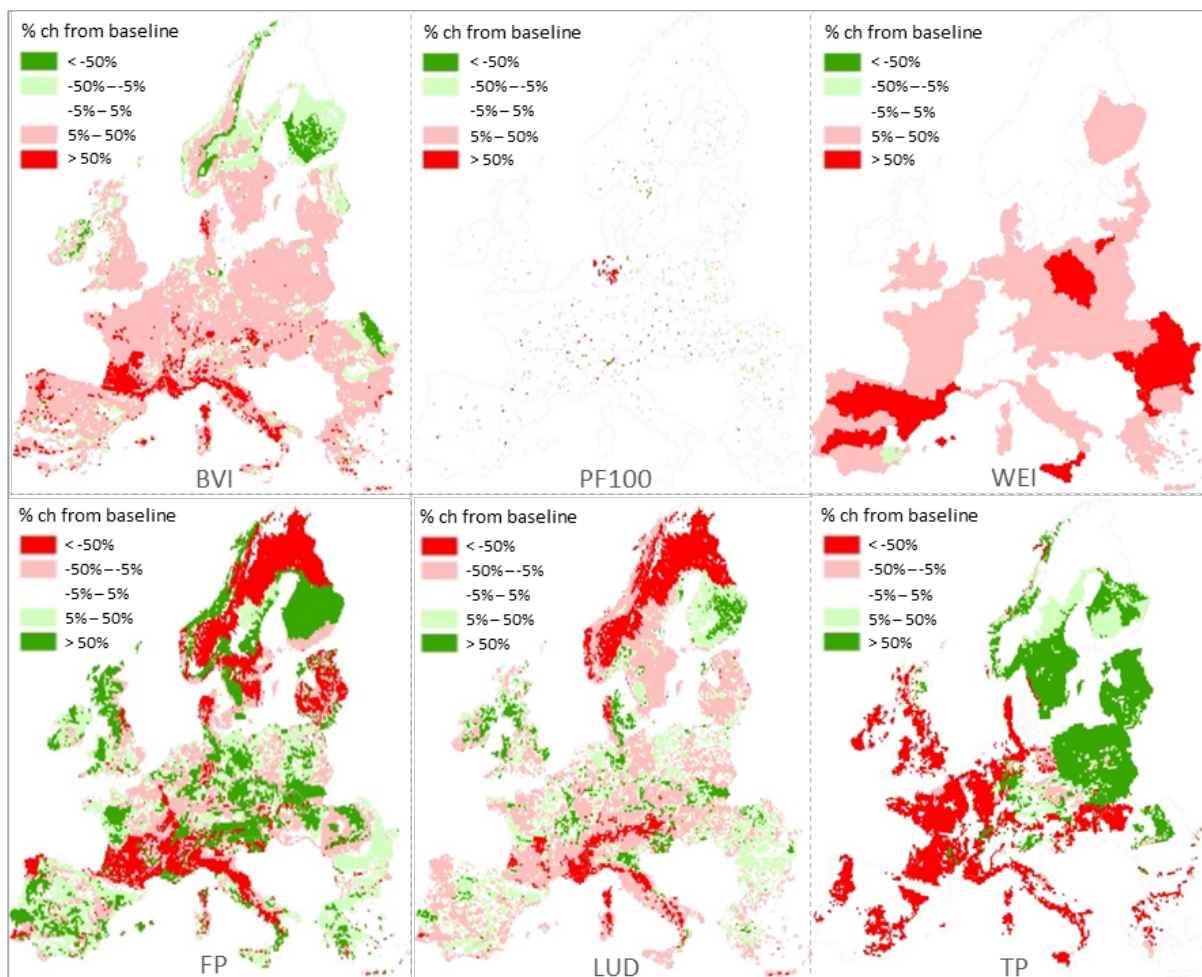


Figure 7: Spatial distribution of the percentage change (from baseline) of nexus impacts in Europe based on grid-level ensemble-mean simulations across the climate scenarios.

Land use diversity shows moderate decline in 53% of the grids across Europe, resulting in a Europe-wide average decline by 13%. Areas with the largest decline (>50%) in land use diversity are concentrated in northern Europe (representing ~12% of Europe's grids). Similar hotspot areas are also found in the Mediterranean (e.g., southeast France and northwest Italy, covering ~3% European grids). Such declines in diversity are often driven by changes in agricultural land use, which has cascading adverse implications on other sectors. For food production, while the Europe-wide average decline is <2%, there are significant variations spatially. A moderate decline in food production is observed in 45% of the grids, while increasing by the same proportion in a similar number of grids elsewhere across Europe. Areas with the largest (>50%) decline in food production are mainly in parts of southern and northern Europe (covering 17% European grids). In contrast, expansion of intensive agriculture in some areas leads to an increase in production by >50% in a quarter of the grids across Europe. Larger proportions of this are distributed across northern (9% of grids) and western (8%) Europe, while the rest in southern and eastern Europe (~3% of grids in each region). These areas are considered as key agricultural land for maintaining Europe-wide baseline level production under the various climate scenarios. However, this has important implications on other sectors including timber production, which declines significantly (by >50%) across most parts of western and southern Europe. This is mainly associated with conversion of forest areas to intensive agriculture to meet Europe-wide food provision priorities. In contrast, a combination of greater yield potential in some areas and overall profitability in other areas lead to an

overall increase in timber production in northern and eastern Europe (particularly in the north) under some of the climate scenarios.

3.3.2 Socio-Economic Change Scenarios

Fig. 8 shows the spatial distribution of potential hotspots of nexus impacts based on grid-based ensemble-mean simulations under the socio-economic scenarios. Unlike the climate scenarios, there are consistent adverse changes in most indicators, albeit with varying magnitudes, across large areas of Europe. The water index shows moderate increase in half of the grids in Europe, leading to a Europe-wide average increase by 41%. However, large areas of southern and eastern Europe (covering ~17% of European grids) are identified as water stress hotspots. Similarly, there is wide spread increase in biodiversity vulnerability and number of people flooded across Europe. This represents a moderate increase in 30% and 20% of the grids, respectively, which lead to a Europe-wide average increase of 6% (biodiversity) and 10% (flooding). Areas such as southern parts of Spain and Portugal, alpine areas in Austria, southeast France, northern Germany and various areas in Italy are identified as hotspots in biodiversity vulnerability, although collectively they represent only a small proportion (just 1%) of grids across Europe. Similarly, flood impact increases by >25% in 3% of grids spread across Europe. Unlike the climate scenarios, there are no or very few grids that experience a reduction in impacts on biodiversity and water. This is mainly driven by the increase in population in some of the socio-economic scenarios, which affects the number of people living within flood plains (hence flood impacts), demand for water (e.g., for irrigation or domestic use, affecting water stress), and land use change (with implications on species distribution).

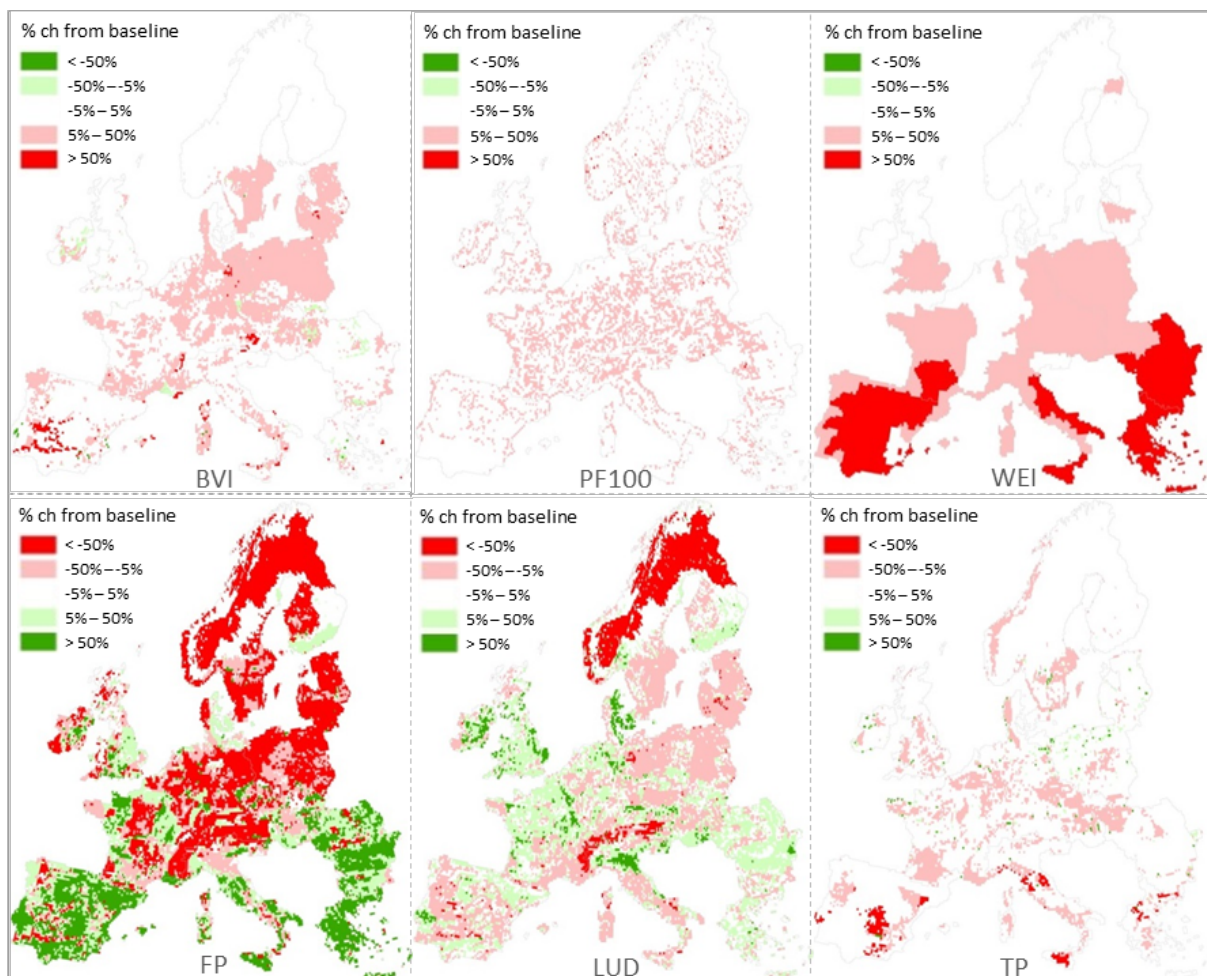


Figure 8: Spatial distribution of the percentage change (from baseline) of nexus impacts in Europe based on grid-level ensemble-mean simulations across the socio-economic scenarios.

While the Europe-wide ensemble-mean food production is projected to increase by just 1%, there is a clear regional divide in the grid-based simulations in terms of the direction of change under the socio-

economic scenarios. It shows moderate increase in 30% of the grids, while declining by the same proportion in 54% of Europe's grids. However, there are significant changes (>50%) in food production, declining in 38% and increasing in 13% of the grids across Europe. The largest reductions mainly occur in northern (18% of grids) and western (11% of grids across Europe) regions. In contrast, the largest increases in production occur in southern Europe (~8% grids), followed by 5% of grids spread across western and eastern Europe. This is mainly a manifestation of the scenarios explored. On the one hand, scenarios with increases in food imports and agricultural yields lead to a reduction in production in less productive areas. On the other hand, scenarios that increase demand through higher population or decreases in food imports result in expansion of intensive agriculture in more productive areas. However, this has implications on other land use indicators such as diversity and forestry, which decline by >5% in 45% and 18%, respectively, of the grids across Europe. Land use diversity is also projected to increase by the same amount in 27% of the grids across Europe.

4. Conclusions and Outlook

The study demonstrated that there are important synergies and trade-offs across the FWLE nexus sectors and regions, and associated major land use constraints in Europe. In particular, there is a significant trade-off between food production and other components of the FWLE nexus, which needs to be recognised and analysed within cross-sectoral adaptation policy formulation (e.g., Karabulut *et al.* 2018; Maes *et al.* 2012; Mouysset 2017; Serrao-Neumann *et al.* 2014). The methodology presented also highlighted the potential benefits of systems integration and nexus approaches considering a multi-sector, multi-scale and multi-scenario perspective and quantitative insights to identify key nexus interactions. This is crucial for fostering synergies and co-benefits and managing damaging trade-offs and conflicts between sectors and regions in order to support sustainable and efficient use and integrated management of natural resources in Europe and beyond that are consistent with the SDGs.

While there is extensive qualitative and now a growing number of quantitative nexus frameworks and modelling exercises, important methodological and policy challenges still remain. In particular, comprehensive and quantitative cross-sectoral integration remains a challenge in terms of application and implementation of nexus approaches and their policy relevance to fully understand and address the highly interconnected sustainability challenges such as in achieving the SDGs (e.g., Liu *et al.* 2018). A holistic view of the complex nexus interactions and associated implications of multi-dimensional future changes (e.g., climate, social, technological, economic, environmental, and policy governance conditions) require major advances in development of integrated quantitative modelling approaches and tools. Key future research directions include broadening current nexus frameworks by incorporating more aspects of the socio-ecological system (e.g., health, energy sectors), considering dynamic feedback between sectors, incorporating wider range of important drivers (endogenous, exogenous), improving issues of scale (spatial, temporal), considering consistent representation of sectoral processes and similar level of model complexity between various sectors, and translating exploratory approaches to decision support tools. Vanham *et al.* (2019) demonstrated that an environmental footprint family analysis can provide key information to assess the water-energy-food-ecosystem (WEFE) nexus and measure progress towards the SDGs. Advances in complex data handling approaches such as emerging data science (also termed synonymously as 'big data') technologies can play an important role in this regard (e.g., Blair *et al.* 2019).

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