Physical and economic consequences of climate change in Europe

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Quantitative estimates of the economic damages of climate change usually are based on aggregate relationships linking average temperature change to loss in gross domestic product (GDP). However, there is a clear need for further detail in the regional and sectoral dimensions of impact assessments to design and prioritize adaptation strategies. New developments in regional climate modeling and physical-impact modeling in Europe allow a better exploration of those dimensions. This article quantifies the potential consequences of climate change in Europe in four market impact categories (agriculture, river floods, coastal areas, and tourism) and one nonmarket impact (human health). The methodology integrates a set of coherent, high-resolution climate change projections and physical models into an economic modeling framework. We find that if the climate of the 2080s were to occur today, the annual loss in household welfare in the European Union (EU) resulting from the four market impacts would range between 0.2–1%. If the welfare loss is assumed to be constant over time, climate change may halve the EU's annual welfare growth. Scenarios with warmer temperatures and a higher rise in sea level result in more severe economic damage. However, the results show that there are large variations across European regions. Southern Europe, the British Isles, and Central Europe North appear most sensitive to climate change. Northern Europe, on the other hand, is the only region with net economic benefits, driven mainly by the positive effects on agriculture. Coastal systems, agriculture, and river flooding are the most important of the four market impacts assessed.

climate adaptation policy | climate impact and adaptation assessment | integrated assessment model | computable general equilibrium

Adaptation is becoming a key issue of post-2012 international climate policy negotiations. The December 2009 Copenhagen Accord (1) establishes that by 2020 developed countries will provide US\$ 100 billion per year to address the needs of developing countries, including funding for adaptation. Indeed, even ambitious mitigation policies [e.g., the 2 °C target proposed by the European Union (EU) and endorsed by the G8 (2, 3)] will need to be complemented by adaptation strategies to lessen the impact of residual warming (4). Europe is preparing for a coordinated adaptation climate strategy from 2013, as set out in the European Commission *White Paper on Adaptation* (5). One of its main conclusions is that much still is unknown about the potential impacts of climate change on the European economy as a whole or with respect to different economic sectors and geographical regions of Europe (6–9).

The quantitative assessment of the economic impacts of climate change is vital for justifying strategies to curb global warming and minimize detrimental consequences. Evaluating the effects of climate change in the very long term is an extremely complex issue because of incomplete scientific methodologies and data gaps. For this reason, the assessment must account for the many sources of uncertainty, including future climate, demographic change, economic development, and technological change.

Most studies (e.g., 10–15) have focused on climate damage functions as reduced-form formulations linking climate variables to economic impacts [usually average global temperature to gross domestic product (GDP)]. Nevertheless, such a top-down approach is unsatisfactory for the following reasons: Damage estimates often are derived from the literature, thus originating from different and possibly inconsistent climate scenarios. They also lack the necessary geographical resolution for assessing regional impacts and prioritizing adaptation policies. Moreover, only the average temperature and precipitation usually are included, ignoring other moments of the probabilistic distribution and other relevant climate variables.

We present here a high-resolution, regionally focused, and integrated assessment of the physical and economic effects of climate change in Europe. The analysis is innovative because it integrates (*i*) climate data with high space–time resolution; (*ii*) detailed modeling tools specific for each impact category considered; and (*iii*) a multisectoral, multiregional economic model. The appraisal presented herein builds on examples of assessments made elsewhere (e.g., for the United States, see refs. 16–20; for a global assessment, see ref. 21).

Five impact categories have been addressed in this study: agriculture, river basins, coastal systems, tourism, and human health. These five aspects are highly sensitive to changes in mean climate and climate extremes. For this study the EU has been divided into five regions to simplify interpretation (Fig. S1): Northern Europe, the British Isles, Central Europe North, Central Europe South, and Southern Europe.

Methodological Framework

The consistent methodological framework that integrates the climate data, physical-impact models, and economic models is shown in Fig. S2. In the first stage, daily and 50-km resolution climate data are obtained from climate models. In the second stage, these data are used as input to run the five physical-impact

models. (See *SI Text* for detailed explanations on the models and Table S1 for their specific climate data input.)

In the third stage, the physical-impact models and their associated direct economic effects are introduced into a multisectoral computable general equilibrium (CGE) model (22), General Equilibrium Model for Energy-Economy-Environment Interactions (GEM-E3 Europe), which models most EU countries individually.

This study has other distinctive features. We have modeled the economic effects of future climate change (projected for the 2080s) on the current economy as of 2010. Several authors have followed this approach (e.g., 23). This quasi-static analysis would be the equivalent of having the 2080s climate in today's economy. The alternative approach (followed, e.g., in ref. 24) would be to model the effect of the future climate on the future economy. Implementing a static approach has the advantage that hypotheses on the future evolution of the economy over the next eight decades are not needed, thereby minimizing the number of assumptions. Moreover, the interpretation of the results becomes simpler. Within this quasi-static economic metrics, we also present undiscounted impacts. Time discounting is a key and controversial issue in evaluating the impacts of climate change (25, 26).

A baseline scenario has been run for 2010 assuming no climate change. The alternative scenario considered the influence of climate change in the economy. The results presented compare the values of welfare and GDP of the climate scenario with those of the baseline scenario.

This study also has estimated "potential impacts" (27), which do not consider public adaptation policies. The assessment of potential impacts in various sectors facilitates the identification of priorities in public adaptation policies. In the models applied in this analysis, only private adaptation actions have been taken into account (e.g., farm level adaptation in agriculture), but no new explicit public adaptation policies have been considered. Although the coastal systems DIVA model uses a more sophisticated cost–benefit framework to determine the optimal level of adaptation, in this study, this option has been disabled to measure the potential impact of sea-level rise (SLR).

Scenarios. We have considered four climate futures for the 2080s (Table 1) to reflect the uncertainty associated with the driving forces of global emissions and the response of climate to greenhouse gas (GHG) concentration. Two global socioeconomic scenarios have been selected from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) (28): the high-emission A2 scenario and the lower-emission B2 scenario (CO_2 concentration of 709 ppm and 560 ppm by the end of this century, respectively). For each SRES scenario, climate output from two state-of-the-art regional climate models (RCMs), nested within a global climate model (GCM), have been selected from the Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects (PRUDENCE) project (29). Daily RCM output at 50-km resolution has been used to drive the physical-impact models. In the following, all climate change numbers refer to a comparison of the 30-y periods 1961–1990 and 2071–2100.

Temperature and Precipitation. The scenarios considered lead to an average temperature increase in Europe between 2.5 °C and 5.4 °C (Table 1). These figures depend on the GHG emission scenario chosen and the climate model used (temperature and precipitation maps appear in Figs. S3 and S4). Hereafter, the climate futures are called "scenarios" and are distinguished by the EU temperature increase: 2.5 °C (B2 HadAM3-HIRHAM), 3.9 °C (A2 HadAM3-HIRHAM), 4.1 °C (B2 ECHAM4-RCAO), and 5.4 °C (A2 ECHAM4-RCAO). Northern Europe is the area with the highest temperature increase in the 2.5 °C and 3.9 °C scenarios, whereas in the 4.1 °C and 5.4 °C scenarios, Central Europe South and Southern Europe would experience the largest temperature increase. The more oceanic British Isles have the lowest temperature increase throughout all scenarios. The global temperature increase of the scenarios is in the range of 2.3–3.1 °C. One A2 simulation shows lower warming than one of the B2 simulations; it should be kept in mind that modeled projections of

Table 1. Summary of socioeconomic and climate scenarios

	Scenario			
	2.5 °C	3.9 °C	4.1 °C	5.4 °C
World population in 2100 (10^{12})	10.4	15.1	10.4	15.1
World GDP in 2100 (10^{12}, 1990 US$)	235	243	235	243
CO_2 concentration (ppm)	561	709	561	709
Δ Temperature (°C)*				
World	2.4	3.1	2.3	3.1
EU[†]	2.5	3.9	4.1	5.4
Southern Europe	2.6	4.1	4.3	5.6
Central Europe South	2.4	3.9	4.4	6.0
Central Europe North	2.3	3.7	4.0	5.5
British Isles	1.6	2.5	3.2	3.9
Northern Europe	2.9	4.1	3.6	4.7
Δ Precipitation (%)*				
EU[†]	1	−2	2	−6
Southern Europe	−7	−15	−13	−28
Central Europe South	2	−2	−4	−16
Central Europe North	3	1	6	−1
British Isles	−5	−2	10	5
Northern Europe	10	10	19	24
Sea level rise (high climate sensitivity) (cm)	49	56	51	59

*Increase in the period 2071–2100 compared with 1961–1990.
[†]European regions: Southern Europe (Portugal, Spain, Italy, Greece, and Bulgaria), Central Europe South (France, Austria, Czech Republic, Slovakia, Hungary, Romania, and Slovenia), Central Europe North (Belgium, The Netherlands, Germany, and Poland), British Isles (Ireland and United Kingdom), and Northern Europe (Sweden, Finland, Estonia, Latvia, and Lithuania).

regional climate change have a larger spread than projections of global change.

The regional precipitation pattern is similar in all scenarios. The Central Europe South and Southern Europe regions would experience annual decreases compared with the 1961–1990 control period, whereas most other EU regions would have positive precipitation changes in all scenarios but with large seasonal differences.

Sea-Level Rise. According to the IPCC (30, 31), the uncertainty range of the projected SLR is wide. Given recent evidence on accelerated SLR (32), we consider only the high-climate-sensitivity case. This case leads to a global SLR in the range of 49–59 cm by the end of the century (Table 1). The high range of SLR of the IPCC Third Assessment Report (TAR), 88 cm, also has been studied for the coastal system impact as a variant of the 5.4 °C scenario.

Results

Agriculture. Because the production and quality of cultivated crops and their use of water are influenced directly by local climate variables and atmospheric CO_2, agriculture is particularly susceptible to climate change (33–36). Agriculture is the main user of land and water and still plays a dominant economic role in many rural areas of Europe. Previous studies have shown that the stress imposed by climate change on agriculture will intensify the regional disparities between European countries (7, 8, 14).

We investigated the response of the distribution of premium and productivity of crops in Europe to potential climate change induced by increased GHG forcing. The assessment linked biophysical and statistical models in a rigorous and testable methodology, based on the current understanding of processes of crop growth and development, to quantify crop responses to changing climate conditions.

We found that the 2080s climate would have a rather dramatic spatial agricultural effect and a serious impact on aggregated regional production (Table 2). In the 2080s the scenarios of lower warming could lead to small changes in EU yields, whereas the 5.4 °C scenario could mean a reduction in crop yields by 10%. All

Table 2. Physical annual impacts in agriculture, river basins, coastal systems, and tourism of 2080s climate-change scenarios in the current European economy

Physical impacts	European regions*					
	Southern Europe	Central Europe South	Central Europe North	British Isles	Northern Europe	EU
Physical impacts as estimated by the agriculture model						
Yield change (%)[†]						
2.5 °C	0	5	−1	−9	37	3
3.9 °C	−12	5	−3	−11	39	−2
4.1 °C	−4	3	2	15	36	3
5.4 °C	−27	−3	−8	19	52	−10
Physical impacts as estimated by the river flooding model						
People affected (1,000s/y)[‡]						
2.5 °C	46	117	103	12	−2	276
3.9 °C	49	101	110	48	9	318
4.1 °C	9	84	119	43	−4	251
5.4 °C	−4	125	198	79	−3	396
Physical impacts as estimated by the coastal systems model						
People flooded (1,000s/y)[§]						
2.5 °C	258	82	345	70	20	775
3.9 °C	456	144	450	136	40	1,225
4.1 °C	313	85	347	86	20	851
5.4 °C	474	158	459	207	56	1,353
5.4 °C, 88 cm SLR	1,091	512	2,398	1,279	272	5,552
Physical impacts as estimated by the tourism model						
Bed nights change (%)[¶]						
2.5 °C	−1	2	2	3	4	1
3.9 °C	−1	3	3	4	6	1
4.1 °C	−2	14	13	14	20	6
5.4 °C	−4	17	16	18	25	7

*European regions: Southern Europe (Portugal, Spain, Italy, Greece, and Bulgaria), Central Europe South (France, Austria, Czech Republic, Slovakia, Hungary, Romania, and Slovenia), Central Europe North (Belgium, The Netherlands, Germany, and Poland), British Isles (Ireland and United Kingdom), and Northern Europe (Sweden, Finland, Estonia, Latvia, and Lithuania).
[†]Yield changes compared with 1961–1990 period and weighted by the country agriculture value added.
[‡]Differences compared with the 1961–1990 period.
[§]Differences compared with 1995.
[¶]Differences compared with 2005.

2080s scenarios show considerable regional disparities in impacts on agriculture. Southern Europe would experience yield losses that would become relatively high under the 5.4 °C scenario—about 25%. The Central Europe regions would experience moderate changes in yield. In all scenarios Northern Europe would benefit from positive yield changes, and, to a lesser extent, the British Isles would benefit in the 4.1 °C and 5.4 °C scenarios. These effects result from the dominance of the longer growing season. A group of countries (e.g., Ireland, Belgium, Germany, France and the Netherlands) may be at risk if limitations on the use of fertilizers in agriculture are considered. Romania would experience higher potential gain, partly because of the considerable weight of agriculture in its economy.

River Floods. River floods are the most common natural disaster in Europe (37), resulting in large economic losses through direct damage to infrastructure, property, and agricultural land and through indirect losses within flooded areas and beyond. The costs arising from floods have increased rapidly during the last decades, although the observed upward trend in flood damage can be attributed largely to socioeconomic factors (38). Global warming generally is expected to increase the magnitude and frequency of extreme precipitation events (39, 40), which may lead to more intense and more frequent river floods.

Estimates of changes in the frequency and severity of river floods are based on simulations using the LISFLOOD hydro-

logical model (41). This model has been developed for operational flood forecasting at the European scale and is a combination of a grid-based water-balance model and a one-dimensional hydrodynamic channel flow-routing model. Because it is spatially distributed, the model can take account of the spatial variation in land use, soil properties, and climate variables. The LISFLOOD model transfers the climate-forcing data (temperature, precipitation, radiation, wind-speed, and humidity) into estimates of river runoff. By using extreme value analysis, changes in flood magnitude at different return periods are derived (42). From the calculated flood inundation depths, expected annual economic damage and the population exposed are estimated using country-specific flood depth–damage functions, information on land use, and data on population density. The projections assume no growth in exposed values and population or adjustments of current flood protection standards and hence consider only the effects of climate change on flood risk.

River flooding would affect 250,000–400,000 additional people per year in Europe by the 2080s (Table 2). The increase in direct damage from river floods in the 2080s ranges from €7.7 billion to €15 billion, more than doubling the annual average damages during the period 1961–1990. In general, the higher the mean temperature increase, the higher are the projected increase in people exposed to floods and the expected damages. The impacts at the regional level vary substantially, deviating strongly from the EU average. Flood damages and people affected are projected to increase across much of Western Europe, the British Isles, and the Central Europe regions. Decreases in flood damage are projected consistently for northeastern parts of Europe because of a reduction in spring snowmelt floods.

Coastal Systems. Coastal regions are areas where wealth and population are concentrated and are undergoing rapid increases in population and urbanization (43, 44). SLR is a direct threat to productive infrastructures and to the residential and natural heritage zones.

The bottom-up coast assessment is based on the Dynamic and Interactive Vulnerability Assessment (DIVA) tool, an integrated impact–adaptation model allowing interaction between a series of biophysical and socioeconomic modules to assess the impacts of SLR (45). A major weakness of earlier studies is that they examined only a subset of the physical consequences of SLR; DIVA allows all the major direct impacts of SLR to be evaluated quantitatively in physical terms. These effects include (*i*) direct impacts on erosion, (*ii*) increased flood risk and inundation, (*iii*) coastal wetland loss and change, and (*iv*) surface salinization. Adaptation is an explicit part of the model, and the benefits of a range of homogenous adaptation options can be explored together with their costs, including options from no protection to total protection, together with intermediate options which characterize more realistic adaptation responses in the context of Europe.

The number of people annually affected by sea floods in the reference year (1995) is estimated to be 36,000. Without adaptation, the number of people affected annually by flooding in the 2080s increases significantly in all scenarios and ranges from 775,000–5.5 million people (Table 2). The British Isles, Central Europe North, and Southern Europe are the areas potentially most affected by coastal floods. However, when adaptation (dikes and beach nourishment) is taken into account, the number of people potentially exposed to floods is reduced significantly.

The economic costs to people who might migrate because of land loss (through submergence and erosion) also increases substantially under a high rate of SLR, assuming no adaptation, and the costs increase over time. When adaptation measures are implemented, this displacement of people becomes a minor impact. This result indicates the important benefit of adaptation to coastal populations affected by SLR.

Tourism. Tourism is a major economic sector in Europe, with the current annual flow of tourists from Northern to Southern Europe accounting for one in every six tourist arrivals in the world (46). Climate change has the potential to alter tourism patterns in Europe radically by inducing changes in destinations and seasonal demand structure (47).

The tourism study simulated the major outdoor international tourism flows within Europe. The study represents an improvement on earlier work because it integrates the climate component of tourist activity (climate suitability was expressed with the tourism climate index, see ref. 48) with the economic analysis of tourist demand flows, considering also seasonality effects in a tourist regional demand model.

For the 2080s, the distribution of climatic conditions in Europe is projected to change significantly. For the spring season, all climate model results show a clear extension toward the north of the zone under good conditions. Excellent conditions in spring, which are found mainly in Spain in the baseline period, could spread across most of the Mediterranean coastal areas by the 2080s. Changes in autumn are comparable to the ones in spring. In summer, the zone of good conditions also expands toward the north but at the expense of the south, where climatic conditions would deteriorate. These results match the findings of earlier studies into the impact of climate change on climate suitability for tourism (e.g., 49).

Southern Europe, which currently accounts for more than half of the total EU capacity of tourist accommodation, could be the only region with a decline in bed nights, estimated to range between 1% and 4% depending on the climate scenario (Table 2). The rest of Europe is projected to have large increases in bed nights, in the range of 15–25% for the two warmest scenarios. The changes in bed nights caused by changing climate conditions can be estimated econometrically, leading to changes in expenditure associated with bed nights. In all climate scenarios there would be additional expenditures, with a relatively small EU-wide positive impact of €4–18 billion, depending on the scenario and climate model used.

A key assumption is that the tourism system has full flexibility in responding to climate change. Climate change can affect overall demand, and the seasonal distribution of tourists is determined exclusively by climate factors. However, if institutional factors (e.g., school holidays) limit that seasonal flexibility, results could be quite different. In that case, for example, Southern Europe might not be able to compensate for the summer losses with gains in the shoulder seasons.

Human Health. Climate change has a range of complex interlinkages with health (50), including direct impacts, such as temperature-related illness and death and the health impacts of extreme weather events. Other impacts follow more indirect pathways, such as those that give rise to water- and food-borne diseases, vector-borne diseases, or food and water shortages.

There is a direct relationship between mortality and temperature that differs by climatic zone and geographical area (51). High ambient temperature is associated with mortality from heat stroke and also illnesses (e.g., cardiovascular diseases). However, rising temperatures also reduce winter excess deaths. The projections of the impacts of climate change on heat-related and cold-related mortality were based on empirical relationships between mortality and current temperature (51–53). The study used daily projected temperature information at a 50-km grid resolution across Europe, combined with country-specific data from socioeconomic scenarios for population and age structure and with background health incidence data for both current and future periods. Impacts were estimated using temperature-response functions, which provide relationships between daily mortality and daily temperature. These functions usually are represented as separate functions for heat and cold effects, reflecting the fact that mortality increases at low or high temperatures above certain threshold levels, i.e., around a broad central range over which there is little response.

In the 2080s, without adaptation measures and physiological acclimatization, the effect of heat- and cold-related mortality changes depends on the set of exposure-response functions used. The range of estimates for the annual increase in mortality (caused by heat and without acclimatization) is between 60,000 and 165,000. Physiological and behavioral responses to the warmer climate would have a very significant effect in reducing this mortality, potentially reducing the estimates by a factor of five. The range of estimates for the decrease in cold-related mortality is between 60,000 and 250,000, although there also may

be a decline in the sensitivity of mortality to cold. It is notable that, in aggregate, the decreases in cold-related mortality may outweigh the increases in heat-related mortality. This result can be understood because, based on the impact functions used in the study, the current baseline climate of Europe is associated with more deaths in the winter than in the summer. The cold- and heat-related impacts are estimated using simple epidemiologically derived functions for daily mortality; however, there are important differences in the impact pathways, linkages with morbidity, exposure patterns, and other determinants between the heat- and cold-related deaths.

Impact on the Overall Economy. The consequences of climate change on the four market impact categories (agriculture, river floods, coastal systems, and tourism) can be valued in monetary terms because they directly affect sectoral markets and—via the cross-sector linkages—the overall economy. They also influence the consumption behavior of households and therefore household welfare.

If the climate of the 2080s occurred today, the annual damage of climate change to the EU economy in terms of GDP loss is estimated to be between €20 billion for the 2.5 °C scenario and €65 billion for the 5.4 °C scenario with high SLR (Fig. 1).

However, the damages expressed in GDP loss underestimate the actual losses. For instance, the repair of damage to buildings caused by river floods increases production (GDP), because it represents a kind of obliged consumption, but does not improve consumer welfare. (Table S2 details the changes in GDP and welfare for all scenarios and market impact categories.) The aggregated impact on the four categories would lead to an EU annual welfare loss between 0.2% for the 2.5 °C scenario and 1% for the 5.4 °C scenario with a high SLR (88 cm) (Fig. 2). The long-term historic EU annual growth of welfare is around 2%. Assuming that the annual loss is constant over time, climate change would reduce the annual welfare growth by between 0.2% and 1%.

EU-aggregated economic impact figures hide a high variation across regions, climate scenarios, and impact categories. In all 2080s scenarios, most regions would undergo welfare losses, with the exception of Northern Europe, where gains in a range of 0.5–0.8% per year are driven largely by the improvement in agricultural yields. Southern Europe would be severely affected by climate change, with annual welfare losses of around 1.4% for the 5.4 °C scenario.

The sectoral and geographical decomposition of welfare changes under the 2.5 °C scenario shows that aggregated European costs of climate change are much higher for agriculture, river flooding, and coastal systems than for tourism (Fig. 3). The British Isles, Central Europe North, and Southern Europe ap-
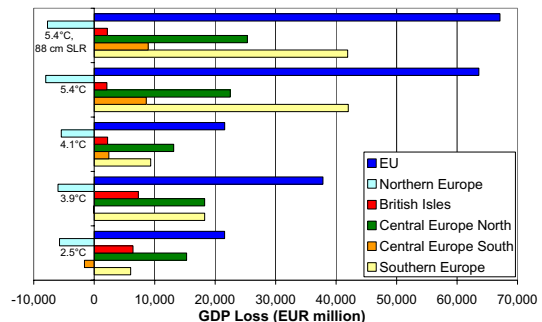

Fig. 1. Annual impact of 2080s climate-change scenarios in terms of GDP loss (in million €). The scenarios are identified by the average EU temperature increase, although temperature is not the only determinant of economic impacts. Impacts are determined by the combination of SRES socioeconomic scenarios and data, the associated emissions scenarios, and the use of alternative climate models, leading to different spatial patterns of the climate variables. These factors explain why, for example, the economic costs are higher in the EU overall and in most regions under the 3.9°C scenario than under the 4.1°C scenario.
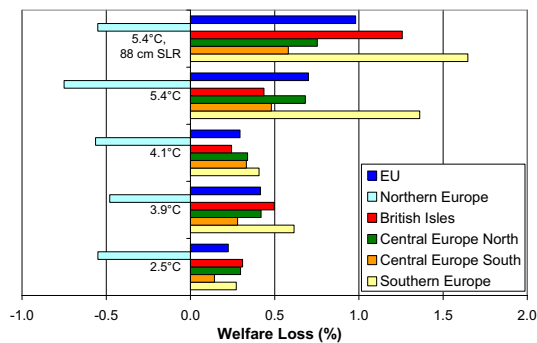
Fig. 2. Annual impact of 2080s climate-change scenarios expressed as percent change in welfare. The scenarios are identified by the average EU temperature increase, although temperature is not the only determinant of economic impacts. Impacts are determined by the combination of SRES socioeconomic scenarios and data, the associated emissions scenarios, and the use of alternative climate models, leading to different spatial patterns of the climate variables. These factors explain why, for example, the economic costs are higher in the EU overall and in most regions under the 3.9°C scenario than under the 4.1°C scenario.

pear to be the most sensitive areas. Moreover, moving from a European climate scenario of 2.5 °C to one of 3.9 °C aggravates the three noted impacts in almost all European regions. In the Northern Europe area these impacts are offset by the increasingly positive effects on agriculture.

The 5.4 °C scenario would lead to an annual EU welfare loss of 0.7%, with more pronounced impacts in most sectors in all EU regions. The agricultural sector is the most important impact category in the EU average, as was found in the United States (17). The significant damages in Southern Europe and Central Europe South are not compensated by the gains in Northern Europe. Impacts from river flooding also are more important in this case than in the other scenarios, with particular aggravation in the British Isles and in Central Europe. In the 5.4 °C scenario with the high SLR (88 cm) variant, which would lead to a 1% annual welfare loss in the EU, coastal systems would become the most important impact category, especially in the British Isles.

Discussion

This study has aimed to estimate the regional distributional implications of climate change in Europe, beyond aggregate impact estimates. We illustrated the feasibility of integrating the relevant scientific disciplines in an "end-to-end" way, ultimately providing estimates of physical and socioeconomic impacts on

the sectoral and geographical scales relevant to the current debate on adaptation in the EU. This multidisciplinary assessment represents an improvement on monodisciplinary assessments (54).

Regarding the lessons learned, one key decision concerns the careful selection of climate scenarios, taking into account the data needed by impacts modelers and the desirability of working with state-of-art climate models while being aware of the variability of climate model data for the same underlying socioeconomic scenario. Making such a decision requires scientific coordination actively involving all impacts-modeling teams as well as climate experts.

Despite the breadth and depth of this study, the results still may be viewed as indicative or merely illustrative because both the issue and the proposed methodology are complex and subject to many caveats and uncertainties. Uncertainties are present in all models of the integrated assessment, both in their input and structural specification. The socioeconomic scenarios driving GHG emissions, the sensitivity of the climate models to GHG concentrations, the specific physical-impact models, and the assumptions regarding economic valuation are all subject to uncertainty, and all are key in influencing the final results.

Adaptation has been modeled to various degrees in the impact models, because the cost–benefit analysis of adaptation strategies is not achievable currently on a European scale. Earlier assessments for the coastal systems indicate that adaptation policies could be particularly cost efficient for this sector (55).

The coverage of impact categories has some limitations, because it does not consider potentially important impacts (e.g., on forestry and transport and energy systems, migration phenomena, and biodiversity losses). The effects caused by climate extremes such as heat waves, storms, and droughts have not been considered explicitly, nor have major economic damages caused by low-probability high-impact events (such as collapse or slowdown of the thermohaline circulation). Furthermore, possible intersectoral effects, which often lead to greater vulnerabilities, are not considered. Thus, this study possibly underestimates the climate impacts on the EU economy.

The next steps in the research agenda consist of the extension of the impact coverage to include nonmarket effects, weather extremes and catastrophic impacts, the modeling of cross-sectoral effects, the cost–benefit analysis of adaptation, the use of dynamic land-use scenarios, and a probabilistic assessment of impacts. Equity issues also could be considered more explicitly and going beyond the standard efficiency analysis by identifying winners and losers in the space and time resolution of the adaptation assessment.

Despite the quasi-static modeling framework of this application, impacts can be interpreted genuinely in annual terms, because the physical-impact models deliver results on a year-
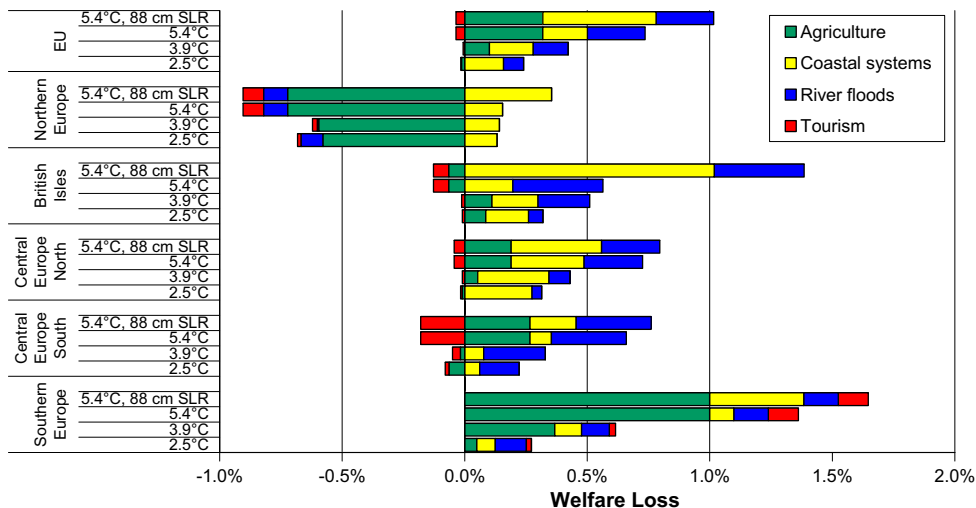

Fig. 3. Sectoral decomposition of regional welfare expressed as percent change.

by-year basis. Assessing the impacts on long-term economic growth would require a truly dynamic multisectoral approach, simulating the economy and climate change to the end of this century and specifically dedicated to addressing the issues missing in the present analysis, such as capital spillovers and path-dependent effects. Such a dynamic setup also would allow a better analysis of the times scales of change of adaptation policy.

In conclusion, there seems to be a need to improve the conceptual framework underlying the multidisciplinary assessment of climate impacts and adaptation, particularly by better integrating the different disciplines in a consistent way, e.g., overcoming the limitations of the standard cost–benefit analysis to include fat-tailed uncertainty (56).

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