Identifying key processes and sectors in the interaction between climate and socio-economic systems: a review toward integrating Earth–human systems

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Abstract

For the purpose of identifying the key processes and sectors involved in the interaction between Earth and socio-economic systems, we review existing studies on those processes/sectors through which the climate impacts socio-economic systems, which then in turn affect the climate. For each process/sector, we review the direct physical and ecological impacts and, if available, the impact on the economy and greenhouse gas (GHG) emissions. Based on this review, land sector is identified as the process with the most significant impact on GHG emissions, while labor productivity has the largest impact on the gross domestic product (GDP). On the other hand, the energy sector, due to the increase in the demand for cooling, will have increased GHG emissions. Water resources, sea level rise, natural disasters, ecosystem services, and diseases also show the potential to have a significant influence on GHG emissions and GDP, although for most of these, a large effect was reported only by a limited number of studies. As a result, more studies are required to verify their influence in terms of feedbacks to the climate. In addition, although the economic damage arising from migration and conflict is uncertain, they should be treated as potentially damaging processes.

Keywords: Earth system model, Integrated assessment model, Socio-economic system, Climate system, Human system

1 Introduction

Earth system models (ESMs) are global climate models (GCMs) that are coupled with biogeochemical components, such as the carbon cycle (Hajima et al. 2012; Kawamiya et al. 2020), and can be employed to simulate climate change for specific greenhouse gas (GHG) emission pathways. ESMs are characterized by transient climate sensitivity to airborne carbon, carbon sensitivity to airborne carbon, and carbon sensitivity to climate change (Friedlingstein et al. 2006), which, in combination, reflect the transient climate response to cumulative carbon emissions (TCRE; Gregory et al. 2009). The TCRE is a crucial parameter for carbon budget estimates that are designed to meet specific temperature targets, such as 1.5 °C or 2 °C set by the United Nations Paris Agreement (Rogelj et al. 2019). When ESMs are run for future climate projections, GHG-emission and land-use scenarios are quantified using the outputs of socio-economic models or integrated assessment models (IAMs; e.g., O'Neill et al. 2016). However, for more complete modeling, this approach may need to be modified to consider the interaction between Earth and human (particularly socio-economic) systems.

Climate change affects a wide variety of human systems. For example, Burke et al. (2015), Carleton and

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Hsiang (2016), and Hsiang et al. (2017) have shown that climate change impacts many socio-economic processes, such as human mortality rates, agricultural production, total factor productivity (TFP), migration, and conflict. Moreover, Diffenbaugh and Burke (2019) concluded that global warming has increased global economic inequality, and Moore and Diaz (2015) pointed out that warming-induced slowing of GDP growth is more significant in low-income countries. However, Beckage et al. (2018) raised the possibility that human behavior could have a significant impact on climate change projections. In this vein, Woodard et al. (2019) reported that economic carbon cycle feedbacks could be of a size comparable with and in the opposite direction of natural climate–carbon cycle feedbacks; thus, they may consequently offset each other. In particular, they decomposed CO_2 emissions by population, gross domestic product (GDP) per capita, energy intensity (energy use per unit GDP), and carbon intensity (CO_2 emissions per unit of energy) based on the Kaya identity (Kaya and Yokobori 1997) and found that GDP per capita was the strongest factor of carbon emissions. GDP per capita is one of the more difficult-to-predict quantities, and it has been claimed that a climate-change-produced gain in GDP per capita would reverse the sign of Woodard et al.'s (2019) main conclusion (Caldeira and Brown 2019).

To consider the interaction between Earth and human systems, one solution is to couple individual models of these systems. One such example is the simple coupled climate–economy system model proposed by Kellie-Smith and Cox (2011), which suggested that historically observed economic growth rates and decarbonization can lead the climate–economy system to experience damaging oscillations. When coupling more complicated models (e.g., an ESM and an IAM), van Vuuren et al. (2012) concluded that the most appropriate coupling approach depends on the situation under analysis and full coupling may not always be the most desirable approach. Indeed, coupling ESMs and IAMs is not an easy task because it requires matching spatial and temporal resolution (Chou et al. 2018), and differences between IAMs' focus on land use and ESMs' focus on land cover should be carefully accounted for (Bond-Lamberty et al. 2014; Robinson et al. 2018). Improving ESMs in terms of their simulations of agriculture and other types of land management is also important (McDermid et al. 2017; Pongratz et al. 2018).

Collins et al. (2015) developed an integrated Earth system and socio-economic model. Previously, Di Vittorio et al. (2014) suggested that using this type of model would moderate the gap between land use in IAMs and land cover in ESMs. Using the same model as Collins et al. (2015), Jones et al. (2018) showed that the inclusion of human-driven responses in an ESM altered both

terrestrial concentration–carbon and climate–carbon feedbacks to increased carbon storage. Other similar models have also been proposed (Sokolov et al. 2005; Yang et al. 2015, 2016; Monier et al. 2018), including a model using an ESM of intermediate complexity (EMIC) instead of a state-of-the-art ESM (Mercure et al. 2018). However, Calvin and Bond-Lamberty (2018) concluded that more research and models were needed to robustly quantify the sign and magnitude of human–Earth system feedbacks.

This study aims to identify the key processes involved in the feedbacks from socio-economic systems to the climate. Given that the most important feedbacks from socio-economic systems to the climate occur via changes in GHG emissions, which in many cases occur via a change in economic growth, we evaluate the impact of these feedbacks in terms of the impact on the economy as a whole. It should be noted that there are other feedback processes linking socio-economic systems to the climate, which are discussed later.

In Section 2, we review previous studies on individual processes and sectors through which the climate affects human or socio-economic systems, particularly in terms of physical and ecological effects. These processes were selected from previous lists of processes/sectors used for impact assessment (e.g., IPCC 2014; Yokohata et al. 2019) based on the impact on the economy as a whole. This section focuses on presenting the results of relatively recent studies, particularly those that have followed the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), although it also refers to some important older studies. Section 3 discusses these findings, and Section 4 provides a conclusion.

2 Feedback processes from climate to socio-economic systems

In this section, after the impact on the whole economy, we discuss the impacts of climate change on eight key processes: land productivity (i.e., cropland and pasture), water resources, sea level rise (SLR) and inundation, natural disasters, other ecosystem services, human health (i.e., labor productivity and disease/health), industry and related economic activities (i.e., energy, infrastructure, tourism and transportation, insurance, and finance), and migration and civil/international conflict. Each subsection describes the physical and/or ecological effects of climate change on the process and the economic and GHG emission effects if available. In the end, we refer to additional topical issues and adaptation if available. Many studies referred to here use Representative Concentration Pathways (RCPs), but some studies use the Special Report on Emissions Scenarios (SRES) scenarios; see Supplementary Information (SI) for their comparison. In

Table 1 Impact of climate change on GDP

Study	GDP impact	Climate change scenario	Model	Note
Stern (2007)	5–20%	BAU	Formal economic models	The costs of mitigation can be limited to around 1% of global GDP each year. There has been criticism on the method of estimating damage and selection of parameter values, including the utility discount rate (see, for example, Cole 2008).
Burke et al. (2015)	23%	RCP8.5 (2100)	–	SSP[*]5
Takakura et al. (2019)	6.6% (3.9–8.6%)	RCP8.5 (2100)	Five ESMs	SSP3, strict mitigation could limit the impact to less than 1%
Nordhaus (1994)	0.60%	2 ℃ increase	DICE	The reference reports a damage function with which we calculated the GDP impacts of 2 ℃ warming.
Nordhaus and Sztorc (2013), Nordhaus (2014)	1.10%	2℃ increase	DICE	The reference reports a damage function with which we calculated the GDP impacts of 2 ℃ warming.
Tol (2018)	0.1–3.0%, 0.9–5.1%, 6.1–6.7%	2.5 ℃, 2.9–3.2 ℃, 5.4–6.0 ℃	Summarizing 27 studies on the impact of the climate on the economy[a]	–

[a]In terms of welfare-equivalent income, [*]Shared Socio-economic Pathway

SI, the basic information of the studies cited are also presented as tables.

2.1 Whole economy

Stern (2007) estimated that for the business-as-usual (BAU) case, the overall costs and risks of climate change will be equivalent to losing 5–20% of GDP, while the costs of mitigation can be limited to around 1% of global GDP each year. In response to this, there has been criticism on the method of estimating damage and selection of parameter values, including the utility discount rate (see, for example, Cole 2008). We should also note that the impact on the economy strongly depends on the scenario and the level of warming. The GDP impacts reported in existing studies are summarized in Table 1. In addition, Tol (2018) showed that warming of up to 1 ℃ had a positive effect on the economy, which is not dramatically different from Ueckerdt et al. (2019), who concluded that 1.9–2.0 ℃ was the economically optimal warming point when considering mitigation and adaptation costs. That is, slight warming could have a positive impact on the economy.

Meanwhile, Roson and van der Mensbrugghe (2012) concluded that changes in GHG emissions were nonnegligible; for example, they found that climate change impacts would lead to a 4.7% reduction of CO_2 emissions worldwide by 2100 in addition to declines in methane (8.4%) and N_2O (7.8%) emissions[1].

2.2 Land productivity

By altering temperature, precipitation, and radiation patterns that influence plant productivity, climate change affects cropland and pasture yields, which are vital to meet the demand for food. Sometimes, the effect of increasing the CO_2 concentration, including the so-called CO_2 fertilization and change in stomatal conductance, is excluded from the impact of climate change, but we include that impact, as climate change is always associated with a CO_2 concentration increase.

2.2.1 Cropland

For the past, Iizumi et al. (2018) concluded that climate change decreased the mean global yields of maize, wheat, and soybeans in 1981–2010 by 4.1%, 1.8%, and 4.5%, respectively, relative to when the preindustrial climate is input. Regionally, Matsumoto and Takagi (2017) found that an inverted U-shaped curve describes the relationship between temperature and rice production and also reported that, when climate change is large, production decreases in many cities, while the impact is relatively low in high-latitude regions.

For the future change, a comparison of multiple global gridded crop models revealed strong negative effects of climate change on crop (wheat, rice, maize, soybean) yields, particularly with high levels of warming at low latitudes and for models that explicitly incorporated nitrogen effects (Rosenzweig et al. 2014). In another study, it was observed for the same four crops that maize and soybean crop yields peaked for relatively slight warming (of 2–3 ℃), while rice yield kept increasing for greater warming (Iizumi et al. 2017)[2]. Under the SRES A1B scenario in 2050, changes in yields of spring wheat,

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[1]For the BAU scenario.

[2]In their study, wheat crops were negatively affected in low-income (which are often located at low latitudes) but not high-income countries (which are often located at mid and high latitudes).

soybean, and maize, relative to the case in the absence of climate change, are projected to be + 1%, − 13%, and − 22%, respectively (Arnell et al. 2016a). Global (tuber) potato yields are also projected to decline by 2–6% by 2055, with larger declines expected by 2085 (2–26%) depending on the RCP scenarios (Raymundo et al. 2018). Consistently, 12–53% (adaptation of sowing date and thermal time requirements to give highest yields) and − 2–27% (a more conservative adaptation of sowing date and thermal time requirements) increases are reported for the European Union (EU) for three SRES scenarios (A1B/B1/B2), and technological progress could even raise these numbers by 17–51% (Zimmermann et al. 2017). Another study on the EU found that, with CO_2 fertilization, crop yield does not decline (RCP8.5, 2030), with the exception of maize (Blanco et al. 2017).

In the full adaptation case[3], it has been estimated that the change in gross agricultural product will be around + 0.06% in 2100, and that it will remain positive until the 2190s (Tol 2002b). Tol (2002b) also reported that each region has its own optimal warming for the agricultural sector, ranging from 0.45 °C to 3.41 °C (depending on the region).

In terms of impacts on GDP, Fujimori et al. (2018) concluded that the negative impact of changes in crop yield on GDP would be 0.02–0.06% (globally, the first and third quartiles) in 2100 even for RCP8.5, and the socio-economic assumption (choice of Shared Socio-economic Pathway [SSP]) had an impact one order larger. A change in crop productivity could affect cropland area and crop price (Thornton et al. 2017; Calvin et al. 2019).

For the impact on total GHG emissions (including pastoralism) by 2050, 0.8 and 0.5 $PgCO_2$ increases, relative to the no climate change case, are estimated for SRES A1 and B1 scenarios, respectively (Bajželj and Richards 2014), which is equivalent to 5 and 3% of total emissions for the two scenarios. The impact of warming on agriculture estimated by Takakura et al. (2019) is slightly positive for RCP2.6, 4.5, and 6.0 but negative for RCP8.5, while Nordhaus and Boyer (1999) estimated the damage for 2.5 °C warming as 0.06% of GDP (output weighted).

For additional information, Reilly et al. (2007) argued that climate change and increases in CO_2 levels will generally have a positive effect, but ozone damage could offset these benefits if it is not strongly controlled. Attention also needs to be paid to subsistence and smallholder farmers, predominantly those in developing countries, which are vulnerable to climate change (Morton 2007).

Additionally, the adaptation cost needed to offset the negative effect of climate change is estimated to be around 7 billion US dollars (USD) per year, including mainly regional target changes (e.g., irrigation efficiency, rural roads, and agricultural research) (Nelson et al. 2009). Smit and Skinner (2002) classified the agricultural adaptation options into four categories: (1) technological developments, (2) government programs and insurance, (3) farm production practices, and (4) farm financial management. They include crop development, weather and climate information systems, and resource management innovations (1); agricultural subsidy and support programs, private insurance, and resource management programs (2); farm production, land use, land topography, irrigation, and timing of operations (3); and crop insurance, crop shares and futures, income stabilization programs, and household income (4).

2.2.2 Pasture and livestock

Climate change is a threat to livestock production due to its influence on feed crop and forage quality, water availability, animal and milk production, livestock diseases, animal reproduction, and biodiversity (Rojas-Downing et al. 2017). In addition, the variety of livestock systems in operation globally complicates the discussion surrounding the effects of climate change (Lopez-i-Gelats 2014; Rivera-Ferre et al. 2016). Inter-model uncertainty (e.g., what Chen et al. (2018) demonstrated regarding carbon sequestration from grazing activity) also remains a problem.

For RCP8.5 in 2050, herbaceous net primary production (NPP) would increase slightly by an average of 3 gC/m^2/year, although overall NPP is expected to decrease (Boone et al. 2018). It was also pointed out that greater precipitation variability, which is a likely consequence of global warming, could have a negative impact on vegetation recovery (Martin et al. 2014). In particular, it was suggested that desertification could have a negative impact (Nardone et al. 2010). For economic impact, globally, under RCP8.5, it is projected that there will be a 7.5–9.6%[4] decline in grazing livestock as a proportion of total stocking in rangelands and an economic loss of 9.7–12.6[4] billion USD by 2050 (Boone et al. 2018).

In addition, many studies (e.g., Olwoch et al. 2008; Gray et al. 2009; Wilson and Mellor 2009) have reported a positive relationship between temperature and the expansion of the geographical range of arthropod vectors

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[3]It assumes substantial changes to agricultural systems with investment in regional/national agricultural infrastructure and policy changes, including large shifts in planting dates, an increase in fertilizer requirements, the installation of irrigation systems, and the development of new crop varieties (Rosenzweig and Parry 1994).

[4]For 7 GCMs

[5]For example, the study by Bett et al. (2017) on tsetse flies, which transmit a range of trypanosome parasites in sub-Saharan Africa. The same study also found that extreme events such as drought promote livestock diseases.

for livestock diseases, but other research has found the opposite[5].

For adaptation, as the impact of climate change is known to be region-dependent, it is pointed out that locking pastoral societies into specified development pathways could be maladaptive (Herrero et al. 2016a). The following are mentioned as adaptation measures: modifying production and management systems (e.g., diversification of livestock animals, application of agroforestry), changing breeding strategies, and improving farmers' perceptions and adaptive capacity (Rojas-Downing et al. 2017). As mitigation measures, the same study mentioned performing carbon sequestration through decreasing deforestation rates and/or improving animal and herd efficiency, reducing enteric fermentation through practices such as improvement of animal nutrition and genetics, improving manure management and fertilizer management, and shifting human dietary trends.

2.3 Water resources

On average, precipitation is increased by global warming. However, the spatial heterogeneity of the rainfall change and increased demand for water (mainly due to increasing populations and economic growth) can cause water scarcity in some regions (this is already evident, and it will further increase in the future).

Two indicators are widely used for assessing water scarcity: water crowding index (WCI)[6] and water stress index (WSI)[6].

For the past, using WSI, it is estimated that 800 million people or 27% of the global population were living under water-stressed conditions in 1960, and this number eventually increased to 2.6 billion or 43% by 2000 (Wada et al. 2011). This number was slightly lowered by Gosling and Arnell (2016) who, using 21 GCMs, estimated that between 1.6 (based on WCI) and 2.4 (WSI) billion people, respectively, were experiencing water scarcity in 2000. However, the main reason for that is considered the increase of human water demand rather than climate change.

For the future, the global population exposed to water shortages (i.e., the situation in which water stress is acknowledged to be a factor limiting development) is projected to further increase significantly. Gosling and

Arnell (2016) reported 37% and 53% population exposure to water scarcity without climate change impact with WCI < 1,000 m^3/capita/year and WSI > 0.4, respectively[7]. In their multi-model study, Schewe et al. (2014), using WCI for RCP8.5, projected that, compared with a population-growth-only scenario, global warming of 2 °C above current temperatures would lead to a 15% increase in the global population facing a severe reduction in access to water resources. They also projected that the number of people experiencing absolute water scarcity (defined as < 500 m^3 per capita annually) would increase by an additional 40%. All of the baseline and different mitigation scenarios considered in the paper resulted in 51–57%[8] global population exposure to water scarcity in 2050 (Hejazi et al. 2014 using WSI), while Hanasaki et al. (2013) using WSI suggested smaller percentages of 25–28%[9] for RCP2.6, 4.5, and 8.5. Arnell and Lloyd-Hughes (2014) using WCI estimated that under RCP2.6, exposure to a higher frequency of flooding would be reduced by around 16% in 2050, and exposure to greater water scarcity would be reduced by 22–24% compared with RCP8.5. The number of people exposed to water resource stress for the SRES A2 scenario is projected to be 10–20% larger than that for the A1B and B2 scenarios (Arnell et al. 2016b).

At least on a regional scale, mitigation and adaptation policies could increase water scarcity. Hejazi et al. (2015) concluded that twenty-first-century United States (US) emissions mitigation could increase water stress (e.g., irrigation for biocrops), and Haddeland et al. (2014) indicated that the water scarcity due to irrigation was significant in parts of southern and eastern Asia in 1970–2000, and it is expected to become even larger in the future.

For economic impact, the water resource damage for 1 °C warming is estimated to be 84 billion USD (Tol 2002a). Under Tol's (2002b) scenario[10], in 2100, this will cause a damage corresponding to around 0.6%[11] of the world GDP. The adaptation measures fall into two areas, management (socio-economic context) and technical solutions, and they are then categorized as follows: wider scope of management, adequate governance and strong institutions, intensification of demand management and supply enhancement, system interconnection and optimal operation, revisiting water rights and water

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[5]For example, the study by Bett et al. (2017) on tsetse flies, which transmit a range of trypanosome parasites in sub-Saharan Africa. The same study also found that extreme events such as drought promote livestock diseases.

[6]WCI is an index of the annual water resources per capita in a watershed, and a WCI threshold of < 1,000 m^3/capita/year is often used as an indicator of water scarcity. WSI is an index of the ratio of water withdrawals to resources, and a WSI of > 0.4 is used to indicate water scarcity. In many cases, WSI > 0.4 results in larger (by 30–50%) population exposure than a WCI threshold of < 1,000 m^3/capita/year.

[7]For the future population of the SRES A1B storyline represented by an IAM.

[8]It depends on the radiative forcing target and tax regime (see Table 4 of Hejazi et al. 2014).

[9]These values vary depending on the RCP scenario.

[10]In Tol (2002b), the scenario used for that study is not described. We assumed that the author used the FUND standard scenario, which is relatively similar to the SRES/B2 scenario (Warren et al. 2006).

[11]Central value

allocation procedures, and early warning and risk management (of drought) (Garrote 2017). For the Maldives, the desalination of water has been mentioned as a "hard"[12] adaptation measure (Sovacool 2012).

2.4 SLR and inundation

Global warming causes additional ocean heat uptake, which causes thermal expansion of the ocean water and the melting of ice and snow, leading to freshwater inflow from land to oceans, both of which contribute to SLR. SLR inundates coastal areas, negatively affecting the local people's lives and economic activities. Relative SLR has a range of potential impacts, including higher extreme sea levels (and associated flooding), coastal erosion, the salinization of surface water and groundwater, and the degradation of coastal habitats such as wetlands (Nicholls 2011).

The satellite observations in 1993–2009 showed that SLR was spatially varying. In the western tropical Pacific Ocean, Southern Ocean, and part of the North Atlantic Ocean, SLR (around 12 mm/year) has increased 3–4 times faster than the global mean (3.2 mm/year) (Meyssignac et al. 2012). For RCP4.5 in 2081–2100 (relative to 1986–2005), SLR of 0.5–0.6[13] m is projected in the northern tropical ocean and southern Pacific Ocean, and 0.4–0.6[13] m is projected for other small island regions (Nurse et al. 2014). These figures indicate the severe future condition for the Pacific small island countries. Under the SRES A1B scenario in 2050, the loss of coastal wetland area and the additional number of people affected by coastal flooding compared with a non-climate change case[14] are projected to be 15% and 1.3 million, respectively (Arnell et al. 2016a).

For economic impact, a study using a static computable general equilibrium (CGE) model found that SLR could have a significant impact on agriculture in 2050 when no protection is applied (Bosello et al. 2007). In that case, a slight GDP loss (0.0–0.1% for eight regions) and small change in CO_2 emissions (−0.02 to + 0.04% for the same regions) was estimated, and for the total protection scenario, those numbers were − 0.10 to + 0.02% (GDP loss) and − 0.34 to + 0.07% (CO_2 emissions). A 25-cm SLR in 2050 results in 0–0.2% (among 16 regions) of GDP direct cost, 0.00–0.11% GDP loss, and − 0.15 to + 0.03% CO_2

emission changes (Bigano et al. 2008); in particular, the impact of SLR on the tourism sector was considerable. Wetland loss for 1 m SLR was projected to be 170,000 km^2, and the protection cost will be 1.06 trillion USD (Tol 2002a).

It was identified that SLR is a particular risk for rice production in Bangladesh, Japan, Taiwan, Egypt, Myanmar, and Vietnam. Using a global rice trade model with an SLR of 0–5 m, it was found that global rice production would fall by 1.60% for the no SLR case and 1.81–2.73% for 1–5 m SLR and that global rice prices would rise by 7.14% and 8.12–12.77%, respectively (Chen et al. 2011).

The global total damage cost by SLR is estimated to reach 200/1000/2000 billion USD for 0.5 m/1 m/2 m SLR, respectively, and for a 0.5-m rise, it is shown that protection (of developed coastal areas) and wetland damage are the two main factors (others considered are dryland damage and mitigation cost) (Anthoff et al. 2010). For a 1-m rise, the Federal States of Micronesia have > 5% of GDP damage, but by protection, 500 billion USD can be saved in 2100 (Anthoff et al. 2010). The inundated area is estimated to be 370,000 (RCP2.6)–420,000 km^2 (RCP8.5), and the affected population is expected to range from 55.3 million (RCP2.6, SSP1) to 106 million (RCP8.5, SSP3) for 2100 (Tamura et al. 2019). Nordhaus and Boyer (1999) estimated the damage for 2.5 °C warming as 0.32% (output weighted) or 0.12% (population weighted) of GDP, indicating that high-income regions have large damages.

For the US, it was found that incorporating site-specific episodic storm surges doubled national damage estimates relative to SLR-only estimates (Neumann et al. 2014). At the city level, Hallegatte et al. (2011) estimated sector-by-sector losses due to an SLR of 2 m above the current sea level for Copenhagen, Denmark in the absence of any protective measures. Transport, postal services, telecommunications, public and personal services, and the housing sector were predicted to experience the greatest direct losses (> 800 million EUR), followed by manufacturing, electricity, gas and water supply, and finance and business activities (400–600 million EUR).

For adaptation, it is suggested that dikes of 1 m in height may reduce the total inundated area by approximately 40% below the no-adaptation baseline under the same RCP scenarios through 2020–2100 (Tamura et al. 2019). The adaptation cost is estimated to be 10 and 50 billion USD in 2050 for new dikes and updated dikes, and for 2100, the cost will be 100–200 (new dikes) and 30–50 billion USD (updated dikes). The benefit−cost ratio is ≤ 1 for new dikes and > 1 for upgraded dikes for both RCP2.6 and 8.5 (Tamura et al. 2019).

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[12]Hard adaptation measures typically employ capital-intensive, large, complex, and inflexible technology and infrastructure, whereas soft adaptation measures prioritize natural capital, community control, simplicity, and appropriateness (Sovacool 2011). Sovacool (2012) reported one hard and one soft measure for water scarcity and other problems (e.g., SLR, tidal inundation; see also the end of Section 2.9.1).
[13]The range appears to be for different regions.
[14]For HadCM3 model (with 3.5 K equilibrium climate sensitivity; Hunter et al. 2019).

2.5 Natural disasters

A warm atmosphere can hold more water (by about 7% per 1 °C), which causes more rainfall. A change in the spatial pattern of rainfall distribution has been observed, with dry areas (generally throughout the subtropics) becoming drier and wet areas becoming wetter (Trenberth 2008), while developing countries and smaller economies are more vulnerable to natural disasters (Noy 2009). Although Bouwer (2011) concluded that anthropogenic climate change to date has not had a significant impact on losses from natural disasters, all projections indicated that there would be an increase in extreme weather losses due to climate change.

Until 2040, however, greater exposure to natural disasters due to population growth and the higher capital value at stake are likely to have an equal or larger effect on disaster losses than anthropogenic climate change (Bouwer 2013). In particular, for tropical cyclones, a review article concluded that a future projection indicates a 2–11% increase in intensity by 2100, with a 6–34% decrease in frequency (with a 20% increase in the most intense cyclones) (Knutson et al. 2010). For RCP2.6 and 8.5, climate change by 2050 would increase exposure to river flood risk for 93–530 and 100–580 million[15] people, respectively (Arnell and Lloyd-Hughes 2014). In an analysis under the SRES A1B scenario, Arnell and Gosling (2016) concluded that, in 2050, 31–450 million people and 59,000–430,000[16] km^2 of cropland would be exposed to the risk of river flooding with doubled frequency. Even without climate change, tropical cyclone damage will be doubled (56 billion USD/year, equivalent to 0.01% of GDP from the current 26 USD billion/year, equivalent to 0.04% of GDP) likely due to future increases in income, and climate change damage doubles that (53 billion/year). That damage was concentrated in North America, East Asia, and the Caribbean–Central America (0.0–0.2% as GDP loss rate, Mendelsohn et al. 2012). Gariano and Guzzetti (2016) presented a map displaying projected future occurrences of four landslide types, suggesting that the frequency of debris flow and shallow landslides would increase in many parts of the world. Cloutier et al. (2016) reported that in Canada, warming would impact permafrost, glaciers, and ice caps, leading to landslides. In a CGE-based analysis, the impact of fluvial floods on GDP was negligible (Takakura et al. 2019).

For adaptation, many studies (e.g., Mercer 2010) have emphasized the importance of integrating disaster risk reduction and climate change adaptation, and Birkmann and von Teichman (2010) concluded that the main barriers to this can be grouped into three categories: (1) spatial and temporal scales, (2) norm systems (e.g., legislative, cultural, or behavioral), and (3) knowledge types and sources. For drought in the Sahel, considering the uncertainty in future climate change, Mortimore (2010) emphasized that the adaptation policies should aim to build on the platform of past achievements and existing local knowledge to enable flexibility and diversity and the protection of assets of small-scale farmers and herders.

2.6 Ecosystem services

Climate change can alter the living environments of many creatures, influencing their existence, which in turn impacts the profit they give us. The functions of ecosystem services can be categorized into four types: supporting (e.g., primary production, nutrient cycling), provisioning (e.g., food, water), regulating (e.g., climate, water, disease), and cultural (e.g., recreation, education) (Millennium Ecosystem Assessment 2005). The Economics of Ecosystems and Biodiversity (TEEB) (2009) mentioned three climate-related issues: coral reef, forest carbon, and investment for climate adaptation. Moreover, Staudinger et al. (2012) for the US identified climate change as having an effect on marine fishery yields, nature-dependent tourism, hazard reduction, and carbon storage/sequestration. Similarly, Grimm et al. (2013) reported that the loss of sea ice, rapid warming, and higher organic inputs affect marine and lake productivity, while the combined influence of wildfires and insect outbreaks reduces forest productivity, mostly in arid and semi-arid western regions of the US. They also reported that ecosystem feedbacks, especially those associated with the release of CO_2 and CH_4 from wetlands and the thawing of permafrost soils, accelerate the rate of climate change.

Shaw et al. (2011) examined how two important ecosystem services in California, carbon sequestration and rain-fed forage production for livestock, were affected by climate change in terms of their distribution and production levels. Based on various climate change scenarios, they predicted that the availability and value of these ecosystem services would decline under most GHG trajectories.

Traditional healthcare systems, which rely on medicinal plants, are also likely to be affected by climate change. In the Himalayan region, persistent climatic variability would alter the habitats of medicinal plants (Maikhuri et al. 2017)[17]. The total ecosystem value at 2005 is evaluated as 1.3 trillion international dollars, and 20–50% of that will experience the climate category transition by 2100 (Watson et al. 2020).

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[15]For 19 GCMs.
[16]For 21 GCMs.

[17]Changes in the phenophases of medicinal plants would require an adjustment to the collection period for these plants, which would go against tradition, while other species would need to be used as substitutes in traditional healthcare systems.

For the future, as an example of hazard reduction, it was suggested that GHG mitigation (to 3.7 W/m^2 target) had potential ecosystem service benefits, on determining the wildfire pattern, of 3.5 billion USD on average in 2005 dollars[18] for 2013–2115 (Lee et al. 2015).

It was concluded that in 2070–2099 (with RCP8.5), for southern California, water runoff (+ 127% to – 60%)[19] and carbon storage (+ 52% to – 31%)[19] were likely to be most significantly affected. Moreover, one-third of high-biodiversity areas were threatened by potential water deficits, and the annual costs of sediment removal were estimated to be around 172 million USD and carbon storage was estimated to be worth 7.5 billion USD (Underwood et al. 2019). For a Mediterranean river basin, it was reported that the availability of drinking water was expected to decrease by 3–49%[20], while total hydropower production would decrease by 5–43%[20]. In addition, erosion control was estimated to be 23% lower, indicating that the costs required for dredging reservoirs and treating drinking water would also increase (Bangash et al. 2013). Impacts of 1 °C warming and CO_2 fertilization are projected to be 439 million and – 50 million USD for forestry and natural ecosystems, respectively (Tol 2002a). The cost of loss of species, ecosystems, landscapes, and so on is estimated to be around 0.04% of GDP in 2100 (Tol 2002b).

For the impact of adaptation on ecosystem services, not only the complex interactions between different ecosystem processes but also tradeoffs between ecosystem services, including the positive effects of increasing temperatures on food and timber production and the longer growing season and the negative effects of more frequent fungal disease and insect outbreaks, were found in cool Finnish regions (Forsius et al. 2013). Recently, ecosystem-based adaptation (EbA), defined as "the use of biodiversity and ecosystem services to help people adapt to the adverse effects of climate change" (SCBD 2009), is advocated and attempted here and there (e.g., Huq et al. 2017; Newsham et al. 2018).

2.7 Human health
Human health can also be affected by climate change. Here, we focus on the impact on labor productivity due to heat stress, the spread of disease, and other health-related issues.

2.7.1 Decrease in labor productivity
Hot working environments affect workers (Tawatsupa et al. 2013; Xiang et al. 2014); heat stress has already

reduced labor capacity to an estimated 90% during peak months over the past few decades (Dunne et al. 2013), with the impact greater for those working outdoors (e.g., agricultural workers) than those working indoors (e.g., office workers; Kjellstrom et al. 2009b). A case study on the steel industry in southern India found that the productivity loss of workers exposed to wet-bulb globe temperatures (WBGTs) above the threshold was significantly higher among workers with direct rather than indirect heat exposure (Krishnamurthy et al. 2017). In construction projects in China, it was found that direct working time declined by 0.57% and idle time rose by 0.74% when the WBGT was increased by 1 °C (Li et al. 2016). Using an econometric approach, Zhang et al. (2018) also estimated the effects of temperature on firm-level TFP, factor inputs, and outputs in Chinese manufacturing plants for 1998–2017 and predicted that in the absence of additional adaptation measures, Chinese manufacturing output would fall by 12% by the middle of the twenty-first century.

For the future, Coffel et al. (2017) estimated that exposure to WBGTs higher than those of recent heatwaves may increase five- to tenfold by 2070–2080 under RCP4.5 and RCP8.5, and under RCP8.5, exposure to WBGTs over 35 °C could amount to over one million person-days per year by 2080. Matthews et al. (2017) investigated the relationship between heat stress, measured by the heat index (see Anderson et al. 2013) and temperature and found that the relationship is nonlinear. They also suggested that under a middle-range population growth scenario with global warming of only 1.5 °C, double the number of megacities could become heat-stressed by 2050, meaning that 350 million more people would be faced with dangerous heat conditions. Kjellstrom et al. (2009b), the earliest study to investigate this topic on a global scale, investigated the relationship between work capacity and climate conditions (measured by WBGT) and estimated the future loss of work capacity caused by climate change for various work intensities. They showed that the greatest absolute losses of work capacity would be in Southeast Asia, Latin and Central America, and the Caribbean (11–27%) for the SRES A2 scenario.

Dunne et al. (2013) also predicted that labor capacity would reduce further to 80% during peak months by 2050 and to less than 40% by 2200 under RCP8.5, with most tropical and mid-latitude zones experiencing extreme heat stress. Under 2 °C target scenarios, this reduction was likely to be smaller, but the labor capacity would still be lower than historical levels. Kjellstrom et al. (2016) found that 30–40% of work capacity during the daylight working hours would be lost by 2085 in some areas for RCP8.5. The outdoor labor capacity during the 2090s would be 0.54 under the highest emission

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[18]Assuming a 3% discount rate.
[19]Depending on GCM.
[20]Depending on scenario (SRES/A2 or B1) and period (2001–30, 2031–2070, 2071–2100).

scenario, and the workday would have to be shifted to 5.7 hours earlier to maintain the labor capacity of the base-year level (Takakura et al. 2018). Reducing work intensity or increasing the frequency of short breaks are effective measures for the prevention of heat-related effects (Kjellstrom et al. 2009b; National Institute for Occupational Safety and Health 2016). However, such interventions reduce work hours and labor productivity (Kjellstrom et al. 2009a; Dunne et al. 2013; Suzuki-Parker and Kusaka 2016; Donadelli et al. 2017; Takakura et al. 2017) and result in economic losses (Roson and Sartori 2016; Donadelli et al. 2017; Takakura et al. 2017; Rezai et al. 2018; Zhang et al. 2018). Many studies have reported an impact of temperature and climate change on socio-economic activities via changes in labor productivity (Kjellstrom et al. 2009b; Hsiang 2010; Roson and van der Mensbrugghe 2012; Dunne et al. 2013; Kjellstrom et al. 2016; Roson and Sartori 2016; Suzuki-Parker and Kusaka 2016; Takakura et al. 2017, 2018; Matsumoto 2019).

Using a CGE model with a BAU scenario, Roson and van der Mensbrugghe (2012) projected GDP losses of up to 6% from the decrease in labor productivity in most regions except Europe, which exhibited an increase in GDP by < 1%. In similar research, Roson and Sartori (2016) found lowered labor productivity for the agricultural sector, which faced a mean variation of – 2.52 to – 17.48% (for 1–5 °C warming), than the manufacturing and service sectors.

Using a CGE model, Takakura et al. (2017) found that total worldwide GDP losses in 2100 would be around 2.6–4.0%[21] for no-mitigation scenarios but that these losses would be less than 0.5% if the 2 °C climate change target was achieved[22]. Even with the introduction of additional adaptation measures, GDP was still projected to suffer severe losses under high-emission scenarios (e.g., 1.0–2.4%[23] under the RCP8.5 scenario) (Takakura et al. 2018). Another CGE study found that total GDP would fall by 0.5–0.9%[24] globally in 2100 under the BAU scenario, although this impact of climate change would differ by region (from + 0.16 to – 5.92%). Moreover, the impact on CO_2 emissions was predicted to be smaller than the impact on GDP (– 0.25 to – 0.45%)[24], and that on temperature was slight (Matsumoto 2019). As another example, using an IAM (including CGE), Roson and van der Mensbrugghe (2012) reported 1.8% and

4.6% GDP loss for 2050 and 2100, respectively due to the change in labor productivity.

Day et al. (2019) summarized the adaptation options into three categories: technical (e.g., air conditioning, ventilation, shading), infrastructural (climate-smart society, economic shift, early warning, education, monitoring), and behavioral (work choice, time shift, individual heat-reducing activities) adaptation measures.

2.7.2 Diseases and other health issues
Climate change has been identified as potentially the most significant global health threat of the twenty-first century (Costello 2009), and it is expected to increase health risks due to increases in the frequency and magnitude of extreme weather events, decreases in air and water quality, and a rise in food-borne, vector-borne, and zoonotic diseases (Séguin 2008; Berry et al. 2014).

For example, Ebi et al. (2017) presented a range of strategies for the detection and attribution analysis of the health impacts of climate change. They discussed three case studies (i.e., heatwave-related deaths, the emergence of Lyme disease in Canada, and *Vibrio* emergence in the Baltic Sea) and concluded that a proportion of climate-sensitive health outcomes can be attributed to climate change. For mosquito-borne diseases, Mordecai et al. (2019) analyzed 11 pathogens transmitted by 15 different mosquito species, including globally important diseases such as malaria, dengue, and Zika, and found that transmission varied strongly and unimodally with temperature, peaking at 23–29 °C and declining to zero at 9–23 °C and 32–38 °C. These effects of temperature on transmission varied between mosquito and parasite species; for example, of the tropical pathogens investigated, malaria and Ross River virus had the lowest thermal optima (25–26 °C), while dengue and Zika viruses had the highest (29 °C).

For future change, Honda et al. (2014) evaluated the heat-related excess mortality arising from climate change under the SRES A1B scenario using a distributed lag nonlinear model. They found that Asia was most vulnerable and that, in some regions, heat-related excess deaths would account for 0.6% of all deaths. Healthcare facilities are thus vital to the management of climate-change-induced health impacts. The increase in the frequency and magnitude of extreme weather events caused by climate change is expected to negatively impact healthcare facilities (Paterson et al. 2014).

Because of climate change, vector-borne diseases can spread to new areas. However, even though initial projections suggested future increases in the geographic range of infectious diseases, more recent models now predict range shifts in disease distributions, with little net increase in area (Lafferty 2009). It is also argued that there was little evidence that climate change had favored

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[21]For RCP8.5 with SSPs 1–3.
[22]Takakura et al. (2017) also reported that the relationship between GDP losses and the rise in global average temperature was roughly linear.
[23]Among four GCMs.
[24]Considering the uncertainty in climate parameters (17th, 50th, and 83rd percentiles are used).

infectious diseases and that many factors can affect infectious diseases, some of which may overshadow the effects of the climate (Lafferty 2009). For example, Béguin et al. (2011) projected that, for the SRES A1B scenario, climate change would have a much weaker effect on malaria than would the increase in GDP per capita. For vector-borne diseases, the responses of both pathogens and vectors to climate change are important. Tol (2002a) estimated that 1 °C warming will globally cause a decrease in deaths by 56,000 but a significant increase in South and Southeast Asia and Africa.

Heat-related excess mortality and occupational health cost are two main factors of impact of warming for all four RCPs (Takakura et al. 2019). A study on the economy-wide impacts of climate change on human health using a CGE model found, for the SRES B1 scenario in 2050, that climate-change-induced health impacts range from + 0.08% to – 0.07%[25] of GDP and from + 0.13% to – 0.18%[25] of CO_2 emissions (Bosello et al. 2006). Another CGE model-based study, Hasegawa et al. (2016a), evaluated the impact of climate change on human health via undernourishment based on two economic measures. These were (1) changes in morbidity and mortality due to nine diseases caused by being underweight as a child, which affect the labor force, population, and demand for healthcare, and (2) the value of lives lost and willingness to pay to reduce the risk. They showed that the economic valuation of healthy lives lost due to undernourishment in response to climate change under a pessimistic scenario based on SSP3 and RCP8.5 was around – 0.4–0.0%[26] of global GDP in 2100, although this differed by region (ranging from – 4.0–0.0%). They also showed that global economic losses associated with the effects of additional health expenditure and the decrease in the labor force due to undernourishment caused by climate change were – 0.1–0.0%[27] of GDP and – 0.2–0.0%[27] of household consumption, respectively (RCP8.5/SSP3, in 2100). Nordhaus and Boyer (1999) estimated the damage of 2.5 °C warming as 0.10% (output weighted) or 0.56% (population weighted)[28] of GDP.

As adaptation measures for the increase in infectious diseases, the following are recommended: (1) further research on the relation between climate change and infectious diseases, (2) improvement of the prediction of the spatial–temporal process of climate change and the associated shifts in infectious diseases at various spatial and temporal scales, and (3) establishment of locally effective

early warning systems for the health effects caused by climate change (Wu et al. 2016).

2.8 Industry and related economic activity
This section covers a wide range of economic activities related to industry, including energy supply and demand, infrastructure, insurance and finance, tourism, and transportation. It was difficult to include manufacturing as a sub-section, as only qualitative assessments of the supply chain were available (e.g., Tenggren et al. 2020).

2.8.1 Energy sector
The energy sector is relatively sensitive to climate change in terms of both supply and demand. Vulnerable portions on the supply side include thermoelectric power, hydropower, and renewable sources such as wind energy. On the other hand, significant variation exists in energy demand—particularly related to the energy used for thermal comfort, including heating, cooling, and de-humidification—between different latitudes. Thus, colder areas may not require as much energy for warming as temperatures increase, while warmer regions will use more for cooling (de Cian et al. 2013). In turn, efforts on climate change mitigation could induce technological development, which positively affects the economy (Matsumoto 2011a, 2011b, 2012).

For the supply side, the water stress resulting from global warming can lead to insufficient water availability, which in turn reduces thermoelectric and nuclear power generation. Similarly, hydropower is expected to exhibit more seasonal variability due to climate change; particularly, in summer, energy generation would decline by around 14% (RCP4.5, 2091–2100) compared with the present generation, which would be a matter of concern for the energy managers (Chilkoti et al. 2017). However, globally, no notable aggregated impacts on GDP are expected in the future when comparing low and high physical impact scenarios, although substantial differences will be observed between regions[29]. In addition, because climate change affects wind speeds, it is likely to influence the generation of wind energy[30] (Pryor et al. 2012).

For the demand side, it is indicated that urban economies in developed (developing) countries need to exhibit a cooling electricity response of 35–90 W/

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[25]Depending on the region.
[26]Mainly from the choice of values of life. Climate and crop model uncertainty is also included.
[27]Climate and crop model uncertainty.
[28]The difference indicates that damages are concentrated in low-income regions.

[29]For example, the maximum achievable hydropower generation might range from – 37% in the Middle East to approximately 20% in the former Soviet Union under RCP2.6 in 2100 compared to the level of 1960–1989, and for GDP, it might range from – 0.11% in Brazil to approximately 0.21% in the former Soviet Union in the RCP2.6 scenario in 2100 relative to the scenario without considering the physical climate impacts (Zhou et al. 2018a).
[30]For example, Pryor et al. (2012) presented evidence of lower intense wind speeds, particularly in the western regions of the US in 2041–2062, but expected no differences in extreme wind speeds relative to 1979–2000 under SRES A2.

°C (2–9 W/°C)[31] per capita as a cooling electricity above room temperature for cooling (interquartile range of estimates), with the difference attributed to the adoption of air conditioning. For heating, the relation becomes less clear, as non-electricity-based equipment can be used (Waite et al. 2017). Because of the rising household incomes and global warming, the increasing adoption of air conditioning by middle-income countries is confirmed by another study, since most of the homes in high-income countries are already equipped with air-conditioning systems (Davis and Gertler 2015). Globally, heating energy demand will decrease by 34% and cooling demand will increase by 72% by 2100, and the impact on global CO_2 emissions is small for heating but significant (some 1.6 $GtCO_2$ in 2100) for cooling based on a reference scenario (Isaac and van Vuuren 2009). Under the SRES A1B scenario in 2050, changes in heating and cooling energy demands are projected to be − 30% and + 73%, respectively, relative to the situation in 2050 in the absence of climate change (Arnell et al. 2016a). While the percentage changes in heating requirements are not significantly different among the SRES A1B, A2, and B2 scenarios, the percentage changes regarding cooling requirements show significant differences (up to around 20%) in the A2 and B2 scenarios compared with the A1B scenario (Arnell et al. 2016b). As with the economic costs, the changes in the global heating and cooling cost per 1 °C warming are estimated to be –120 and 75 billion USD, respectively (Tol 2002a). The impact on GDP is expected to be − 0.34% for RCP8.5 due to changes in energy demand for space heating and cooling systems, and most of them are attributable to additional investment cost for introducing heating and cooling technology (Hasegawa et al. 2016b). The monetized impacts of global warming on cooling/heating demand are globally negative for all four RCPs under the socio-economic assumptions of SSP1–5 (Takakura et al. 2019).

Adaptation options, such as increasing plant efficiency and replacing system types and fuel switches, are mentioned as effective alternatives to reduce the assessed vulnerability to changing climate and freshwater resources (van Vliet et al. 2016). Behrens et al. (2017) compared four adaptation strategies of power generation to water supply: further switch to seawater cooling, retrofitting of plants to dry air cooling, early retirement of existing power plants, and cancelation of planned plants in favor of renewables. They found that increased future seawater cooling would ease some pressures, highlighting the need for an integrated, basin-level

approach in energy and water policy. Some other options are mentioned by Rübbelke and Vögele (2011), van Vliet et al. (2012), Zhou et al. (2018b), and Davide et al. (2018), who analyzed the adaptation options regarding water (conservation/harvesting/recycling/distribution, irrigation [and its efficiency], desalinization), infrastructure (transport, electrification, multipurpose dams), renewable energy, energy efficiency, health (early warning systems, medical services), living conditions (buildings, heating/cooling, water heating), information and education, and food (food storage, livestock) under the Sustainable Development Goals[32].

2.8.2 Infrastructure

Energy, transport, industrial, and social infrastructure is usually constructed to have a long lifespan, meaning it can potentially be vulnerable to long-term changes in the climate.

Here, as we could not find global assessments, we mention some city/country-scale analyses. The costs associated with damage to critical infrastructure due to climate extremes in Europe could be three times higher than the figure in 1981–2010 of 3.4 billion EUR per year by the 2020s, six times higher by the 2050s, and more than 10 times higher by 2100 with the assumed bias-corrected climate projections under the SRES A1B emissions scenario (Forzieri et al. 2018). It has also been reported that greater damage and/or the earlier failure of pavement in the US is expected under the RCP8.5 and 4.5 climate change scenarios (Gudipudi et al. 2017). Moreover, the incorrect selection of materials for US pavement infrastructure could lead to additional costs of approximately 13.6, 19.0, and 21.8 billion USD by 2010, 2040, and 2070, respectively, under RCP4.5, increasing to 14.5, 26.3, and 35.8 USD billion, respectively under RCP8.5 (Underwood et al. 2017). In addition, from 2015 to 2099, damage to Alaskan public infrastructure would cost approximately 5.5 billion (2015 USD, 3% discount) under RCP8.5 and 4.2 billion USD under RCP4.5, most of which is for roads and buildings[33] (Melvin et al. 2017).

Here, the potential adaptation options considered for infrastructure include increased diameter culverts and drainage systems (against flooding in roads and runways), base-layer modification and thermosyphon installation (permafrost thaw, roads, and runways), modified binder/sealant application, and base-layer strengthening (precipitation, roads, and runways), increased diameter roof drainage systems (precipitation, buildings), and

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[31]Depending on the city.

[32]Furthermore, they proposed a framework connecting adaptation, mitigation, and sustainable development.
[33]However, the costs are reduced to 2.9 and 2.3 billion USD when proactive adaptation is applied for the same scenarios (Melvin et al. 2017).

base-layer modification and thermosyphon installation (permafrost thaw, railroads).

2.8.3 Tourism and transportation

Weather and climate conditions are important determinants of travel times and destinations for leisure and recreation. Thus, global warming can have a significant impact on the tourism industry.

For the present status, the existing literature has found that cold-weather activities may be at greater risk due to climate change, especially skiing (Steiger et al. 2019), while there might be increased opportunities for warm-weather activities (Hewer and Gough 2018). Another survey on the weather preferences of French tourists revealed that tourists generally show a high tolerance for heat and even to heatwaves, while rainy conditions are a disincentive to travel (Dubois et al. 2016).

For the future projections, tourism will grow in the future, and the influence of changes in population and income is expected to be larger than that from climate change (Hamilton et al. 2005). It is important to note, however, that there are significant gaps in knowledge when predicting future tourism trends, including outdated climate science, climate models, and climate change scenarios; inconsistent assessments between different regions; and a lack of assessment methods for weather sensitivity and potential impacts of climate change for outdoor recreation and tourism activities (Hewer and Gough 2018).

The transportation sector also faces indirect impacts of climate change. Obradovich and Rahwan (2019) showed that moving from freezing temperatures to 30 °C increased vehicle miles traveled by over 10% in the US and increased public transit trips by nearly 15%, while temperatures beyond 30 °C had little influence on these measures. As a result, over 1 trillion cumulative vehicle miles traveled and 6 billion public transit trips in the US are expected due to global warming under RCP8.5. In contrast, climate change could also lower water levels, making traditional river transport less reliable, as in Canada's Mackenzie River (Du et al. 2017). Global warming melts sea ice in the Arctic, increasing accessibility for shipping (Ng et al. 2018), and the risks facing Arctic aviation and marine transportation could be assessed using the Arctic Climate Change Vulnerability Index, combining exposure, sensitivity, and adaptive capacity (Debortoli et al. 2019). The transportation sector is also increasingly vulnerable to climate change in coastal areas, islands, and other places exposed to flooding[34]. Shifts in tourism patterns as well as agricultural

production may also affect passenger and freight transport indirectly (Koetse and Rietveld 2009).

Regarding the potential economic impacts or the resulting CO_2 emissions, Berrittella et al. (2006), using a world CGE model under the SRES B1 scenario, evaluated the economic implications of climate-change-induced variation in tourism demand and predicted regional variation in GDP of − 0.3–0.5%[35] and CO_2 emissions of − 0.001–0%[35] in 2050. As an example of impacts through disasters, disruption costs in Newcastle upon Tyne in the United Kingdom due to a 1-in-50-year event leading to pluvial flooding could be 66% higher by the 2080s, although interventions could lead to a 32% reduction in travel delays (Pregnolato et al. 2017).

For adaptation, Scott and Becken (2010) pointed out that climate change adaptation research on tourism is significantly delayed compared with other economic sectors, with low awareness of climate change and less strategic planning in anticipation of future changes in climate. They also claim that the tourism industry has shown its relatively high adaptive capacity in the sector to the shocks but that knowledge of the capacity to cope with future climate and the broader environmental impacts and societal ramifications remains insufficient. Scott et al. (2012) listed technical, managerial, policy, research, educational, and behavioral adaptation measures for tourism businesses and emphasized the climate change challenges that exist in tourism to provide implications and suggestions for policy-makers to reduce the climate-related risks or to take the advantage of relevant opportunities.

2.8.4 Insurance and finance

Increased disasters will lead to insurance claims, and thus, the premiums should be raised. It is pointed out that climate change can have negative impacts on the affordability and availability of insurance, slow the growth of the industry, and become a greater burden to governments and individuals (Mills 2005).

As a past example, Cannon et al. (2020), in their analysis of post-Katrina New Orleans in the US, argued that uninsured or underinsured homes in cities prone to flooding have a greater risk of facing both flooding and higher insurance premiums due to climate change.

A future projection of flood insurance premiums in the Netherlands concluded that the premiums may increase considerably as a result of socio-economic and climate changes but that this increase would be very region-specific (Aerts and Botzen 2011). It is also reported that the expected "climate value at risk" for global financial assets was 1.8% under a BAU emissions scenario (16.9% for the 99th percentile), falling to 1.2%

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[34]For example, in Caribbean Small Island Developing States, a rise in temperature could disrupt transport operations, and some airports may be affected by more frequent coastal inundation due to climate change (Monioudi et al. 2018).

[35]For eight regions.

(9.2% for the 99th percentile) under a 2 °C scenario (Dietz et al. 2016). A study using an agent-based climate–macroeconomic model predicted that banking crises would be more frequent in the face of climate change (by 26–248%) and that propping up insolvent banks would lead to an annual fiscal burden of around 5–15% of GDP, doubling the ratio of public debt to GDP (Lamperti et al. 2019). Dafermos et al. (2018) argued that the liquidity of firms is likely to deteriorate, leading to higher default rates and damaging both financial and non-financial corporate sectors. They also predicted that climate-induced financial instability may have a negative influence on credit expansion, worsening the overall impact on economic activity, and that introducing a green corporate quantitative easing program could reduce this instability and slow global warming.

In the longer term, due to the decreased availability and affordability of insurance coverage, insufficient adaptation in areas of increasing risk could threaten the concept of insurability itself (Herweijer et al. 2009). In developing countries (Linnerooth-Bayer and Mechler 2006), particularly for agriculture (Nnadi et al. 2013), insurance will work as an adaptation measure.

2.9 Migration and civil/international conflict

It is commonly assumed that climate change will heavily impact patterns of human migration and conflict via shortages of resources (e.g., food, water), although it is difficult to assess the economic damage arising from this. In addition, at present, it is difficult to project future trends in the frequency and scale of migration and conflicts.

2.9.1 Migration

A global survey found that climatic conditions strongly influenced migration for the period 2011–2015 by increasing the severity of drought and the chances of armed conflict (Abel et al. 2019).

The following studies are examples of regional migration in the past. A study on the Indian Sundarbans assessed the environmental, economic, and social factors that spurred migration and identified environmental factors as the most important (Guha and Roy 2016). In rural Ethiopia, it was indicated that the migration of men for employment increased with drought and that land-poor households were most vulnerable, while the movement of women for marriage decreased with drought (Gray and Mueller 2012). Similarly, in Burkina Faso, Henry et al. (2004) suggested that residents of drier regions were more likely to participate in both temporary and permanent migration to other rural areas and that short-term drought tended to increase long-term migration to rural areas and decrease short-term migration to distant destinations. In rural Pakistan, Mueller et al. (2014) found that flooding, a climate shock that

requires extensive relief efforts, had a modest to insignificant impact on migration, while heat stress consistently increased the long-term migration of men when no relief systems were introduced, driven by the negative effect on farm and non-farm incomes. On the other hand, Shayegh (2017) suggested the possibility that the migration of skilled people due to climate change may reduce local income inequality.

Land degradation due to climate variability is an indirect effect that can trigger migration. For example, it is suggested that land scarcity and degradation are linked to out-migration in general and to migration from the forest frontier of northern Guatemala in particular (López-Carr 2012). Good soil quality significantly reduces migration, particularly temporary labor migration, in Kenya but marginally increases migration in Uganda (Gray 2011). In low-lying island countries, there is growing consensus that international migration should be planned for and coordinated (Hauer et al. 2020). In Malé, the capital of the Maldives, more than 50% of respondents believed that future SLR was a serious challenge at the national level and they considered migration to other countries as a potential option in response to this, although many other factors (e.g., cultural, religious, economic, and social factors) are believed to play an important role in migration-related decision-making (Stojanov et al. 2017).

McLeman and Smit (2006) and Tacoli (2009) argued that migration could be an adaptation measure; labor migration could be a particularly good opportunity to utilize migration to promote adaptation to climate change (Barnett and Webber 2009). For the Maldives, the development of artificial islands (such as Hulhumalé) and coral propagation around existing islands are mentioned as hard and soft adaptation strategies for climate change (Sovacool 2012).

2.9.2 Civil and international conflict

Water and food shortages, and significant deterioration of the living environment caused by climate change, can in turn lead to raiding or conflicts. For the past, a survey on global- and country-scale analyses reported that an increase of 1 standard deviation in temperature or rainfall raises interpersonal violence and intergroup conflict by 4% and 14%, respectively (Hsiang et al. 2013), while policymakers have been warned against drawing general conclusions from current data (Bernauer et al. 2012; Hendrix 2017; Adams et al. 2018). Another global survey pointed out that in western Asia in the period 2010–2012, when many countries were undergoing political transformation, the effect of climate on conflict occurrence was confirmed (Abel et al. 2019). It is also reported that the risk of armed conflict was greater in the presence of climate-related natural disasters in countries

characterized by ethnic division (Schleussner et al. 2016). Moreover, it is reported that transboundary water disputes are also potential flashpoints for conflict in a number of regions around the world, with climate change and associated variability in the weather increasing the uncertainty surrounding access to clean water (Kreamer 2012). The global association between extreme weather events and civil conflict was also observed for droughts in Somalia[36] (Maystadt and Ecker 2014). In the Horn of Africa, Solomon et al. (2018) demonstrated that conflict had a strongly negative impact on the environment and that climate variability exacerbated the impact of this conflict.

For future warming, experts agree that the climate can affect organized armed domestic conflict but claim that other drivers, such as low socio-economic development and poor state performance, are more influential. On average, for the 2 °C scenario, the number of experts expecting "negligible change" is similar to the total of those selecting "moderate increase" and "substantial change," while for the 4 °C scenario, the numbers of experts selecting the three answers are similar to each other (Mach et al. 2019).

For adaptation, a research study on Bangladesh mentioned the possibility that adaptation projects can potentially harm others and intensify violent conflicts and claimed that the project planners and practitioners need to become more aware of this fact (Sovacool 2018). Another study on Kenyan drylands also argued that consideration of the political dimensions of local adaptation is needed for climate change adaptation policies to be successful and that conflict is not an external factor inhibiting local adaptation strategies but a part of the adaptation process (Eriksen and Lind 2009). On the other hand, also in (northern) Kenya, it is argued that promoting adaptation includes reducing the level of conflict and insecurity. In addition, the following three key recommendations are mentioned: strengthening of inter-communal conflict prevention and resolution mechanisms, establishing a regional framework that promotes pastoral mobility across international borders, and reducing the availability of small arms through intergovernmental agreements and harmonized disarmament efforts (Schilling et al. 2011).

3 Discussion: interactive coupling of Earth and human systems

We have reviewed a plethora of existing studies on representative important sectors and processes. While we

were of course unable to cover all or most studies, we were able to review a considerable number of excellent studies. In addition, it is also possible that existing studies contain gaps and/or biased results. Thus, although in this section, we attempt to draw some conclusions from the review performed in the previous section, we need to do so carefully. In addition, we need to be careful in comparing studies using the relatively simple damage function approach and those using process-based modeling.

As reviewed in Section 2, many processes and sectors experience non-negligible physical or ecological impacts due to climate change. However, identifying those processes/sectors that are most important in terms of the interaction between Earth and socio-economic systems is difficult, because there is no established approach for comparing these processes/sectors. The most effective strategy for evaluating the potential feedbacks to the climate could be to compare consequent changes in GHG emissions, but very few studies have addressed this. Thus, we compared the impact on GDP, thinking that GHG is roughly proportional to GDP (i.e., assuming that other conditions are not affected by a GDP reduction of up to 1%). Table 2 summarizes previous quantitative assessments of the impact on GHG emissions and GDP. Many of the studies cited in this table employed a CGE model, meaning that the impacts were evaluated after the propagation of the shock for the economy as a whole. The second column from the right indicates the importance of the process/sector in terms of its GDP or GHG impacts, and the rightmost column displays the feasibility based on the authors' judgment.

For GHG emissions, among the sectors for which literature is available, those related to land productivity (i.e., cropland and pasture) have the strongest effect. These sectors have a relatively low impact on GDP, but the resultant change in land cover is 2–3%[37], and that in land-use emission is 8–13%[38] (Bajželj and Richards 2014). In addition, changes in land cover can influence the physics of the land surface, including albedo and evapotranspiration, as well as carbon absorption. Changes in land surface conditions can affect fire occurrence, which can lead to other physical and biochemical changes. Other studies have also suggested the importance of changes in land cover and management (Brovkin et al. 2013; Luyssaert et al. 2014; Harper et al. 2018). Hence, this sector should not be ignored when considering the interaction between Earth and human systems. In modeling, cropland allocation is typically determined using the suitability based on land conditions (Ramankutty et al. 2002; Di Vittorio et al. 2016). Areas with high

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[36]Using the data of 1997–2009, Maystadt and Ecker (2014) also estimated that an increase of 1 standard deviation in drought intensity and length in Somalia would increase the likelihood of conflict by 62%, with conflict arising from changes in livestock prices and the establishment of livestock markets.

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[37]SRES B1 (2%) and A1 (3%) (relative to the no climate change case).
[38]SRES B1 (8%) and A1 (13%) (relative to the no climate change case).

Table 2 GHG emissions and GDP changes caused by each process and sector

Section	Process/ sector	CO₂/GHG emission reduction (%) (negative value means GHG emission increase)	GDP loss (%) (negative value means GDP growth)	Remarks	Importance (in terms of GHG or GDP impacts)*	Feasibility of modeling**
2.2.1	Agriculture	3 and 5[a]	0.02–0.06[b], 0.13 (0.17)[c], 0.06[d]	Feedback via land cover change (albedo, carbon flux, etc.)	H	E
2.2.2	Livestock		0.01[e]	Feedback via land cover change and changes in livestock number	M	E
2.3	Water resources	–	0.6[d]	–	M	M
2.4	SLR	0.0–0.15[f], – 0.04–0.02[g]	0.32 (0.12)[c], 0.0–0.1[f], 0.0–0.03[g]	Life-threatening	M	M
2.5	Natural disasters	–	Negligible[h], 0–0.2[i]	Life-threatening	M	M
2.6	Ecosystem services	–	0.17 (0.10) [c1], 0.4[d1]	–	M	D
2.7.1	Labor productivity	0.25–0.45[j]	2.6–4.0[k], 0.5–0.9[j] 1.8[l], 4.6[l], 1.0–2.4[m]	–	H	E
2.7.2	Other health issues	– 0.13–0.18[g]	0.10 (0.56)[c], 0.0–0.1[n], – 0.08–0.07[g]	For VSL*** (mortality): 0.0–0.4%[n], 0.17%/°C[c,o]	M	M
2.8.1	Energy	0 (2050), –1.1 (2100)[p]	0.2 (0.3)[d2], 0.0–0.2[h], 0.34 (0.03)[q]	No notable aggregated impacts (supply)[r]	M	M
2.8.2	Infrastructure	–	0.01–0.02[s] (EU), 0.1–0.2[t] (US)	-	L	M
2.8.3	Tourism and transportation	0–0.001[u]	– 0.5–0.3[u]	Almost no change as a whole	L	D
2.8.4	Insurance and finance	–	–	5–15% needed to rescue insolvent banks[v]	H	D
2.9.1	Migration	–	–	Welfare impact	–	D
2.9.2	Conflict	–	–	Life-threatening	–	D

*High (H): > 1%, Medium (M): 0.1–1%, Low (L): < 0.1%

**Easy (E), Medium (M), Difficult (D). This is based on the authors' judgment considering the modeling framework

***Value of statistical life

[a]Bajželj and Richards (2014): 5 and 3 for SRES A1 and B1 scenarios

[b]Fujimori et al. (2018), RCP8.5, SSP 2, 2100, CGE

[c]Nordhaus and Boyer (1999) output weighted (population weighted) for 2.5 °C warming, CGE; c1: settlement and ecosystem were merged in their evaluation

[d]Tol (2002b), 2050 (central case); d1: for ecosystem; d2: 2050 (2100): demand for heating [0.4(0.7)] + for cooling [– 0.2(– 0.4)]

[e]Boone et al. (2018) divided by GDP in the IIASA SSP dataset (https://tntcat.iiasa.ac.at/SspDb/dsd)

[f]Bigano et al. (2008), 2050 SLR of 25 cm, CGE (range shows regional difference)

[g]Bosello et al. (2006), CGE (range shows regional difference)

[h]Takakura et al. (2019), CGE; e1: among the scenarios (RCP-SSP)

[i]Mendelsohn et al. (2012)

[j]Matsumoto (2019) BAU, 2100, CGE

[k]Takakura et al. (2017) BAU, 2100, CGE

[l]Roson and van der Mensbrugghe (2012). 1.8% and 4.6% for 2050 and 2100 (IAM including CGE)

[m]Takakura et al. (2018): RCP8.5 with reasonable time shift (< 3 h) as adaptation

[n]Hasegawa et al. (2016a) RCP8.5/2.6, 2100, CGE

[o]Bosworth et al. (2017) for VSL (7 × 10 million USD/person)

[p]Isaac and van Vuuren (2009): 0 (at 2050) and 0.32 (at 2100) PgC (their Fig. 10), the latter of which was divided by 28.8 PgC of RCP8.5 in place of their reference scenario (of 3.7 K warming in 2100)

[q]Hasegawa et al. (2016b) CGE, in 2100 with RCP8.5 (RCP2.6)

[r]Zhou et al. (2018a) (CGE)

[s]Forzieri et al. (2018), divided by GDP (http://sres.ciesin.org/final_data.html)

[t]Underwood et al. (2017), divided by GDP (https://sedac.ciesin.columbia.edu/data/set/sdp-downscaled-gdp-a1a2b1b2-1990-2100/data-download)

[u]Berrittella et al. (2006), CGE (SRES A1, 2050)

[v]Lamperti et al. (2019), BAU, agent-based model

– No data from our review

suitability are allocated in order so that the total crop yield (estimated using an agricultural crop yield model) satisfies the food (and biofuel) demands given from another source (e.g., a socio-economic model). The crop type to plant is then chosen to maximize the profit (e.g., Meiyappana et al. 2014; Hasegawa et al. 2017). Models

could be further improved through model intercomparisons (e.g., Prestele et al. 2016; Lawrence et al. 2016).

The effect of the livestock sector has been assessed to be more moderate than that for the agricultural sector, and an estimated GDP impact of 0.01%. However, raising livestock generates relatively high GHG emissions, particularly CH_4 and N_2O (Herrero et al. 2016b). The manner for modeling this sector is in many cases simpler than that used for cropland (e.g., Yokohata et al. 2020), indicating there is more potential for sophistication. In Bajželj and Richards (2014), total agricultural (including pastoralism) GHG emissions, including net forest cover, tropical pristine forest cover, and land-use change emissions, were estimated as 3% and 5% for the SRES B1 and A1 scenarios (relative to the no climate change case), respectively. This is large compared with other sectors/processes (Table 2), and as this sector is a point of contact between humans and natural systems, the sector is considered to be one of the most important in coupling human and Earth system models.

In addition to agriculture and livestock, the impact of labor productivity on GHG emissions appears to be relatively significant (0.25–0.45%). Considering that Matsumoto (2019), using a simpler approach, resulted in a smaller GDP impact than Takakura et al. (2017), it is possible that the GHG impact was underestimated in Matsumoto (2019). Considering the difference in numbers reported by these studies, the GHG impact of labor productivity could be comparable with that of the agricultural sector if Takakura et al.'s (2017) model is used. To incorporate this effect, the easiest way is to use the simplified (linearized) relationship between temperature and labor productivity for each of agriculture, manufacturing, and service sectors presented by Roson and Sartori (2016), as attempted by the example in Matsumoto (2019). The energy sector can also have a significant effect, causing a 1% increase in GHGs, mainly due to increasing cooling demands. In Isaac and van Vuuren (2009), demand was calculated as a product of the number of households who owned air conditioners and the unit energy consumption that was determined with cooling degree days[39] and income. It should be noted that there could be some inter-sectoral interaction, such as between energy demand and labor productivity (via using air conditioning).

In terms of GDP, finance may have more impact than labor productivity, with Lamperti et al. (2019) reporting that 5–15% of GDP would be needed to bail out insolvent banks. However, they employed an agent-based economic model to arrive at their estimates; when this type of model is not available, it would be difficult to quantify this effect.

Other processes that have been reported to have potentially large impacts are water resources, SLR and inundation, natural disasters, ecosystem services, disease, and other health issues, although most of these have only been supported by a small number of studies each. Thus, more research is needed for firm conclusions to be drawn. In contrast, infrastructure, tourism, and transportation are predicted to have a relatively small impact. However, it should be noted that a process or sector that has a limited global impact on socio-economic systems does not necessarily have a negligible regional impact. Indeed, from an impact assessment perspective, regional impacts may be more important, although this was not the main focus of the current study. Of the five processes/sectors (i.e., water resources, SLR, natural disasters, ecosystem services, disease, and other health issues), ecosystem services may be the most difficult to model due to their wide variety.

For life-threatening processes such as disease, migration, and conflict, although there are some examples to evaluate the monetary damage assessments (which causes feedbacks to the climate via GDP and then emission changes), it is difficult to assess all the effects to the climate. Here, we presented some examples of other approaches knowing it is difficult to obtain quantitative information on the amount of feedback that could be given to the climate. For disease and health issues, a larger impact was reported when the value of statistical life (VSL) was employed to predict additional mortality, but this does not directly impact GDP, and monetizing the value of human life is controversial. Thus, we may need more discussion when comparing the impact on GDP and the VSL. However, we should not underestimate the importance of processes that are difficult to discuss in terms of their impact on GDP. For example, natural disasters and conflict can expose a large number of people to danger, and migration can have a number of deleterious impacts (e.g., poverty [through the loss of assets], discrimination, and the loss of identity) that may not be easy to monetize. Possibly the most representative example of this may be small Pacific island countries, who stand to lose a significant proportion of their territory due to the effects of climate change. In addition, to incorporate migration and conflict in economic models, more knowledge of their causes and consequences is required. For some studies, cases with adaptation were also evaluated, but originally, the cases without adaptation should be first evaluated and incorporated into the model (in this case, a human–Earth system model), and then, the effects of adaptation should be evaluated using the model.

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[39]Cumulative temperature over 18 °C.

Although not mentioned in Section 2 or Table 2, another possible source of large uncertainty would be human behavior. Beckage et al. (2018) showed such a possibility leading to behavioral uncertainty of a comparable magnitude to physical uncertainty. However, the large uncertainty is not a result of the accumulation of many processes but a choice in the equation to calculate for human behavior; three types (linear, logistic, and cubic) of equations were applied despite the fact that the theory of planned behavior generally uses a linear functional form. Thus, we expect follow-up studies.

As noted above, this is a current overview, but as also noted, some sectors' assessments are based on a small number of studies, and in some cases, there are no global assessments on the impact on GDP and GHG emissions. Thus, we need to accumulate more studies for each sector to draw solid conclusions.

4 Conclusions

In this study, we reviewed the impacts of climate change on processes and sectors that were selected from a list of impact assessment studies based on their potential to cause feedbacks to the climate. We focused primarily on recent quantitative studies; although it was not possible to review all of these, we reviewed a sufficient number to overview how a specific process/sector is affected by climate change and the extent of its impact on the economy and subsequently the climate by evaluating its relative importance in terms of GHG emissions and GDP. For GHG emissions, we identified land productivity, particularly agriculture, as a key process with the additional benefit of high modeling feasibility, while labor productivity (in terms of both GHG emissions and GDP) and the energy sector (GHG) were also found to play important roles. We also identified water resources, SLR, natural disasters, ecosystem services, and disease and other health issues as having a non-negligible impact on GDP and/or GHG.

To incorporate life-threatening processes such as disease, migration, and conflict, a solely economic impact assessment may be insufficient, because even though they are obviously vulnerable processes, it is difficult to estimate their monetary costs. In addition, the finance sector is likely to have a large impact on GDP, but conventional CGE models may be unable to incorporate this, so more sophisticated models, such as agent-based economic models, should be considered. Based on the results of this review, we intend to look at coupling Earth and socio-economic models in future work.

Abbreviations
BAU: Business as usual; CGE: Computable general equilibrium; DICE: Dynamic Integrated Climate-Economy (model); EbA: Ecosystem-based adaptation; EMIC: Earth system model of intermediate complexity; ESM: Earth system model; GCM: Global climate model; GDP: Gross domestic product; GHG: Greenhouse gas; IAM: Integrated assessment model; IPCC: Intergovernmental Panel on Climate Change; RCP: Representative Concentration Pathway; SI: Supplementary information; SLR: Sea level rise; SRES: Special Report on Emission Scenarios; SSP: Shared Socioeconomic Pathway; TCRE: Transient climate response to cumulative carbon emissions; TEEB: The Economics of Ecosystems and Biodiversity; TFP: Total factor productivity; US: United States; USD: US dollar; VSL: Value of statistical life; WBGT: Wet-bulb globe temperature; WCI: Water crowding index; WSI: Water stress index

5 Supplementary Information
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Additional file 1.

Authors' contributions
All three authors contributed to literature survey. XS wrote the energy, infrastructure, tourism, and transportation parts. KM wrote the human health part. KT wrote all other parts including the Introduction, Discussion, and Conclusion. All authors read and approved the final manuscript.

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Declarations

Competing interests
The authors declare that they have no competing interests.

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