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## LETTER

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Supplementary material for this article is available [online](#)

### Abstract

Ecosystem service assessments facilitate the valuation of nature and support decision-making. Ecosystem services are connected to climate; however, ecosystem service values affected by climate change remain unclear. We mapped global ecosystem service values totaling ~1.3 trillion international dollars for 2005. Transitions in Köppen–Geiger climate classes projected with General Circulation Models under the four IPCC Representative Concentration Pathways (RCP) were modeled providing 20 climate scenarios. The mapped global ecosystem service values were combined with the 20 climate scenarios in order to identify where and how much of the global ecosystem service value is within a climate class transition. By 2050, 252–375 billion international dollars of ecosystem service value (20%–30% of total value) are in a Köppen–Geiger climate transition for both RCP 2.6 and 8.5 scenarios. In RCP 2.6, the 2015 Paris Agreement carbon emission scenario target, Köppen–Geiger climate transitions stabilize after 2050. However, in the RCP 8.5 scenario, ecosystem service values amounting to 467–632 billion international dollars (37%–50% of total value) are in a Köppen–Geiger climate transition by 2085. These results provide an inclusive global overview of climate change impact on evaluated ecosystem services that affect populations and economies.

### Introduction

Climate change affects ecosystems functioning and their value to both humans and natural systems (Nelson *et al* 2013). Climate change, according to the International Panel of Climate Change (IPCC), is long-term and measurable change in climate characteristics (UNFCCC–United Nations Framework Convention On Climate Change 2011). The Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services (IPBES 2019) assessed direct drivers of change (natural and anthropogenic) for ecosystem function and structure and showed that climate change is among the top drivers for any ecosystem realm (i.e. terrestrial, fresh water, or marine); future climate change scenarios will increasingly affect ecosystem services (ESs). The global economy has become more intermingled (UN 2015), and this globalization has increased the importance

of global assessments of available resources, change, and impacts, especially related to the environment. In order to assess changes and impacts, global, spatio-temporal data are required (Salafsky and Wollenberg 2000).

Global, spatially-explicit ES assessments were pioneered as a construct to value the environment by calculating a monetary value for resources used either directly or indirectly to support decision-making (Costanza *et al* 1997). Governments are making directives to establish ES assessments of their jurisdictions (Kubiszewski *et al* 2017). With government mandates, ES assessments will need to be accessible to civil servants who may or may not have any background in ES theory. Schägner *et al* (2013) conducted a review of ES valuation papers through 2011 that map ES values and categorized the studies on topic, application, and geographic extent or scale. Of the reviewed case studies, only five studies mapped ES values at the global extent.

Since the review in 2011, six other studies mapped ES values globally (Ghermandi and Nunes 2013, Costanza *et al* 2014, Li and Fang, 2014, Kubiszewski *et al* 2017, Sannigrahi *et al* 2018, Song 2018), but the outputs were not published preventing incorporation in future or other analyses by the broader scientific community.

A number of studies combined ES assessments with climate change (e.g. Raymond and Brown 2011, Landis *et al* 2013). They modelled the climate change using General Circulation Models (GCMs), which provide possible changes in temperature and precipitation patterns as a result of increased greenhouse gas concentrations. A combined ES-GCM framework helps governments during the decision-making process to quantify the economic impact of climate change on ecosystems (Grimm *et al* 2016). While many studies have combined aspects of ES and climate change (e.g. Raymond and Brown 2011, Grêt-Regamey *et al* 2013, Landis *et al* 2013, Grimm *et al* 2016, Runting *et al* 2017), these studies focus on either specific geographic areas using Regional Circulation Models or specific services. Runting *et al* (2017) did not identify any studies evaluating climate change and multiple ecosystem services at the global scale in a review through 2014.

Any climate can be classified based on temperature and precipitation (Köppen 1918, Geiger 1954). Due to climate change, the climate at a specific location can shift from one climate class to another, to which we will refer as a *climate class transition*. Within the field of ES and climate change, there is a considerable lack of knowledge on the percentage of ES value in a climate class transition until the end of the century. Significant transitions would indicate that local or federal governments would need to make decisions regarding mitigation or a change in management of ES. The aim of this paper is to contribute to the overall understanding of global spatially explicit ES values and the percentage of those values in a climate class transition. This information could be used to assist governments in decision-making for ES management under different climate change scenarios. This paper asks: (1) *what is the global spatial pattern in ES values?*; and (2) *how much of the ES value is within a transition in climate class?*

This paper is the first to present the ES values and percentage of ES values in climate class transitions that are global, temporal, and spatially explicit. We also provide detailed information related to data and methodology in the supplemental information is available online at [stacks.iop.org/ERL/15/024008/mmedia](https://stacks.iop.org/ERL/15/024008/mmedia), and we provide data online via <https://doi.org/10.5281/zenodo.3515435>.

## Approach

The study is separated into three main sections: assessing ES values for 2005, modeling climate class

transitions up to 2085, and calculating the percentage of ES values in a climate class transition. The first two sections are independent of each other, while the final section requires their results.

## Global ES assessment

A new global, spatially explicit ES assessment was required for this study because previous studies have not released the supporting spatial data, calculations, and resulting maps (e.g. Costanza *et al* 1997, Ghermandi and Nunes, 2013, Costanza *et al* 2014, Li and Fang 2014, Kubiszewski *et al* 2017, Sannigrahi *et al* 2018, Song 2018). ES assessments are made up of categories (e.g. Provisioning, Regulating, Habitat, and Cultural), which consist of ES (e.g. Food, Climate Regulation, Life Cycle Maintenance, Recreation and Tourism). ES are composed of subservices (e.g. livestock, carbon storage, nursery and refugia, tourism), which are calculated by various valuation methods.

The global ES assessment workflow consists of the following steps: (1) inventory the ecosystem subservices and services in ES assessments; (2) homogenize the inventory; (3) reduce the inventory to those ecosystem subservices that are mappable and calculable; (4) preprocess the data; (5) apply spatial disaggregation; and (6) compute total ES values. Table 1 provides detailed information for the ES assessment, including the category, service, and subservices used. This ES assessment is constructed of four categories with eight ES, and nineteen subservices. For each subservice, data provider, year of valuation, data description, and calculation are summarized. Supplemental information 1 describes the data used in ecosystem subservices in detail. Supplemental information 2 summarizes the inventory process applied to the ES assessment (steps 1 through 3).

During the data collection phase of the ES assessment, the year 2005 was selected as a baseline due to data availability. Most of the spatial data required for the assessment had temporality near to or from 2005. More recent data was not nearly as complete for a global assessment. For the majority of the ESs valued, there is tabulated information with the lumped dollar value for each country, and there is spatial information (e.g. land cover or mapped presence) to disaggregate the lumped value over the country (Supplemental Information 3 provides a visualization of disaggregation methods). Twenty-three public databases provided statistics and global spatial coverage for the ES valuation (table 1) (Costanza *et al* 1997, Spalding *et al* 1997, UNEP-WCMC 1999, UNEP-WCMC and Short 2003, Freiwald *et al* 2005, NUS Consulting Group 2006, Nachtergaele and Petri 2008, Ruesch and Gibbs 2008, Tol 2009, UNEP-WCMC, World Fish Centre, WRI and TNC 2010, van der Ploeg and de Groot 2010, Wada *et al* 2011, FAO

**Table 1.** Description of ecosystem categories, services, and subservices used in this ES assessment.

Category	Ecosystem service	Subservice	Date provider	Year	Data description	Value calculation description	Value (million international dollars)	Sources of error							
Provisioning services	Food	fish (wild and farmed)	fish	FAO (2013); VLIZ (2012)	2005	total production value including industrial, commercial, recreational, subsistence; and mariculture, aquaculture, and other farming (FAO Table A4)	value/area	6.12	production may not extend the entire area; fresh water areas are not included						
		fresh water fishing													
		sea plants/vegetable food								FAO (2013); VLIZ (2012)	2005	total aquaculture production value of aquatic plants (FAO Table A5)	value/area	0.39	production may not extend the entire area
		livestock								FAO (2014, 2015)	2005	30-arc-min grid of animal density (buffalo, cattle, goat, pig, poultry, sheep); \$ per live weight tonne; average weight of animal	\$/tonne * #/ha * tonne/#	1,065,330.00	average animal weight; no differentiation between dairy vs meat in animal population
		game (elk, deer, bear, other, water fowl)								FAO (2013); Nachtergaele and Petri (2008)	2005; 2004–2008	game production value; land cover	value/area	0.38	production area
		dairy production (traditional and organic)								FAO (2014, 2015)	2005	Total whole milk gross production by cow, sheep, and goat by country; livestock density	value * density/population proportion	175,923.00	no differentiation between dairy vs meat in animal population
		crops and cereals (traditional and organic)								FAO and International Institute for Applied Systems Analysis (2012)	2000/2005	Summation of wheat, rice, maize, sorghum, millet, tuber crops, cassava and other roots, sugar beet, sugarcane, pulses, soybean, rape, sunflower, groundnut, oil palm, olive, and cotton; spatial disaggregated based on suitability of growth using rainfall, irrigation, and land agronomic capabilities	value	529.64	See Fischer et al. (2008) for details

Table 1. (Continued.)

Category	Ecosystem service	Subservice	Date provider	Year	Data description	Value calculation description	Value (million international dollars)	Sources of error
		fruit production (from orchards; traditional and organic)	FAO (2013); Nachtergaele and Petri (2008)	2005; 2004–2008	fruit production value; land cover	value/area	21.75	production area
		berries (non-cultivated)	FAO (2013); Nachtergaele and Petri (2008)	2005; 2004–2008	berry production value; land cover	value/area	0.93	production area
		mushrooms	FAO (2013); Nachtergaele and Petri (2008)	2005; 2004–2008	mushrom production value; land cover	value/area	0.95	production area
Provisioning services	Water supply	industrial use	Wada et al. (2011); NUS Water Consulting Group (2006)	2005	industrial water demand; cost of water charged to consumers	demand * value * measure conversion	0.03	prices are not available for all countries; used global average for those not available; unclear where the water originates
		drinking water	Wada et al. (2011); NUS Water Consulting Group (2006)	2005	domestic water demand; cost of water charged to consumers	demand * value * measure conversion	0.02	prices are not available for all countries; used global average for those not available; unclear where the water originates; all domestic demand, not just drinking water
	Raw materials	timber and fiber for pulp production timber production, sustainable energy: fuel wood	non-food forest product	FAO (2013); Nachtergaele and Petri (2008)	2005; 2004–2008	wood export value; forests	value / area	18.57
		fiber: wool	FAO (2014, 2015)	2005	30-arc-min grid of animal density (sheep); \$ per tonne wool; average weight of wool from a sheep	\$/tonne * #/ha * tonne/#	2,362.76	Wool weight; dairy vs meat vs fiber use of animal
		fiber: leather and fur	SADC (2014); FAO (2014, 2015)	2005	price per tonne of leather; 30-arc-min grid of animal density (sheep); tonnes of hides for buffalo cattle, goat, sheep	value * density / population proportion	17,107.50	Hide weight; dairy vs meat vs fiber use of animal

Table 1. (Continued.)

Category	Ecosystem service	Subservice	Date provider	Year	Data description	Value calculation description	Value (million international dollars)	Sources of error	
Regulating services	Climate regulation	carbon storage	Hiederer and Kochy (2011); Ruesch and Gibbs (2008); Tol (2009)	2000	global biomass carbon map; global carbon soil map; value	carbon * value	10,267.60	see Hiederer and Kochy (2011); Ruesch and Gibbs (2008); Tol (2009)	
	Moderation of extreme events	storm protection	Costanza et al. (1997); Spalding et al. (1997); UNEP WCMC and Short (2003)	2005	values; mangrove and seagrass coverage	value * area	13.65	value; coverage incomplete	
Habitat services	Life-cycle maintenance	nursery service refugia for migratory and res. species	nursery and refugia	UNEP WCMC (1999); UNEP WCMC, World Fish Centre, and TNC (2010); Costanza et al. (1997); van der Ploeg and de Groot (2010); Freiwald et al. (2005)	2005; 2010; 1999; 1997; 2007	coral reefs; turtle nesting sites	value * area	7.47	value; coverage incomplete
Cultural services	Recreation and tourism	recreation tourism ecotourism hunting and fishing	potential tourism	World Bank (2014); Geofabrik GmbH Karlsruhe (2016)	2005; 2016	international tourism expenditures; lodging locations	value * tourism lodging proportion	723,681.00	Missing national dollars spent; beds per lodging type
	Cultural heritage	social and cultural values		FAO and International Institute for Applied Systems Analysis (2012); IUCN and UNEP WCMC (2013); van der Ploeg and de Groot (2010)	2000; 2012; 2010	GAEZ protected sites; World Heritage Sites; TEEB cultural service general values for onshore and offshore	((gaez U WHS) * onshore value) + (marine area * offshore value)	100.25	Undervaluation due to global values; inclusion of man-made sites

and International Institute for Applied Systems Analysis 2012, Hiederer and Köchy 2011, VLIZ 2012, FAO 2013, IUCN and UNEP-WCMC 2013, FAO 2014, SADC Trade Organization 2014, World Bank 2014, IUCN and UNEP-WCMC 2015, FAO 2015, Geofabrik GmbH Karlsruhe 2016). The published dollar values were supplemented with estimates when direct statistics were not available. Statistics for other years than 2005 were adjusted for inflation to represent the 2005 value. The assessed area of the global spatial mapping was limited to terrestrial areas and their exclusive economic zones, excluding Antarctica. Exclusive economic zones, the marine extent controlled by governments (VLIZ 2012), were used because governmental statistics do not include international waters. The total assessed area is  $2.9 \times 10^8 \text{ km}^2$ , where exclusive economic zones account for half of the assessed area.

The methodology followed in this paper differs in three main ways from previous publications (e.g. Costanza *et al* 1997, Sutton and Costanza 2002, van der Ploeg *et al* 2010, Kettunen *et al* 2012, Li and Fang 2014). First, ES values were not based on ecozones, but were calculated in order to have individual subservices and their values for each pixel with length 10 km in the mapping area (See supplemental information 3). This facilitates the use of the ES values for different analyses whether based on ecozones, climate class, or governmental jurisdictions, among others. Second, this paper uses production values in international dollars to calculate and map ES. Production values were selected because they are representative data as opposed to proxy data. Proxy data are based on one variable, such as land cover/land use, in order to approximate the ES value for an area (Schägner *et al* 2013). Production values from the FAOStat Database represent the monetary value of producing a commodity (FAO 2015). This is the most complete data available globally to assign real economic values to ESs. Where production values or other data required for the calculation are unavailable, the subservice was omitted, i.e. approximations are avoided as much as possible. When missing information becomes available in the future, the subservices can be calculated. Supplemental information 2 summarizes the inventoried subservices and categorizes those that can be calculated but are missing data. Third, only those ES that are determined to benefit society are included. ES that would subtract from the ES value total are considered disservices and not included. Such services tend to focus on clean-up costs. Detailed reasoning and support of the methodology is available in the supplemental information 1, while supplemental information 2 summarizes the inventoried subservices and categorizes whether they are included or excluded and if they are calculable or not.

**Table 2.** Köppen–Geiger climate classification definitions from Köppen and Geiger (1954).

Major	Minor		Definition
	Precipitation	Temperature	
A			Tropical
B			Arid
C			Temperate
D			Continental
E			Polar
	f		Without dry season
	m		Monsoon
	s		Dry summer
	w		Dry winter
	W		Desert
	S		Semi-arid
	F		Frost
	T		Tundra
		h	Hot
		k	Cold
		a	Hot summer
		b	Warm summer
		c	Cold summer
		d	Very cold winter

Note. Köppen and Geiger 1954. *Nach der Wondkarte: Klima der Erde*, 1:16 million. Darmstadt, Germany: Justus Perthes.

## Climate class transitions

The well-known climate classification of Köppen and Geiger (1954) distinguishes five major classes (tropical, desert, temperate, continental, and polar climates), which are subdivided into 31 minor climate classes by precipitation and/or temperature values in specific months. For example, the minor Köppen–Geiger Climate Class (KGCC) Ca stands for a continental climate with a hot summer. See table 2 for the major and minor labels. Transitions from one KGCC due to climate change are termed *KGCC transitions* in this paper. KGCC transitions can occur as a major transition, for example from polar (E) to continental (D), but also as a minor transition, such as from a ‘temperate climate without a dry season and with hot summers’ (Cfa) to a ‘temperate climate with dry and warm summers’ (Csb). These KGCC are connected to the ES as some climates are more suitable for specific ES.

We computed KGCC transitions over the 21st century from existing output of climate models in two steps. Firstly, the KGCC was determined for each year based on 30 year average statistics from the daily temperature and precipitation fields in the GCM output. This resulted in an annual time series of the global spatial distribution of the minor climate classes between 2005 and 2099. Secondly, the spatial distribution of the transition in KGCC was determined by comparing the KGCC for each year with the climate map in 2005, which provided a time series of global

maps where the climate class is projected to shift. We will refer to these as *transition maps* that is the change in KGCC for that year relative to 2005. In addition, this two-stage method was applied to CMIP5 climate projections (Warszawski *et al* 2014). We used 20 projections based on the four RCP scenarios and five GCMs (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, NorESM1-M). These 20 projections were selected as they cover a wide variety of climate change projections and model uncertainty and thus provide us with the full ensemble spread of all CMIP5 models (Warszawski *et al* 2014). Daily temperature and precipitation fields from these five GCMs were bias corrected using the WATCH forcing dataset (Hempel *et al* 2013).

### Assessing ES values in a KGCC transition

We calculated the ES area and the ES value that is in a KGCC transition for each year between 2005 and 2099. The overlay of the time series of the global transition map with the mapped global ES in 2005 expressed in monetary terms provided the ES value in the areas with KGCC transitions over time. We did this for each of the eight ESs, five GCMs, and four RCPs. This resulted, for example, in an annual time series of the Food ES that is in a KGCC transition according to RCP 4.5 and the Nor-ESM1-M climate model. To determine the model uncertainty, we summarized the annual time series of ES value by the minimum, mean, and maximum values between the five GCMs. We performed this summary for each RCP and ES separately over the time period.

The time series analysis shows the global total ES in a KGCC transition, but it does not quantify the area and ES value in all the possible shifts in climate class, such as Cfa to Aw. To that end, we created a transition matrix of climate classes in 2005 versus climate classes in 2099, which shows the mean ES value in a KGCC transition over all GCMs. We created these transition matrices for each of the RCPs and eight ES. Post-processing of the transition matrices calculated the total ES value in KGCC transitions by KGCC for 2005 and 2085 for RCP 2.6.

The results of this assessment facilitate analysis of ES values in KGCC transitions by providing where and when transitions occur; which KGCC transition occurs; and the quantity of ES value within those transitions. We do not calculate the direction of change (i.e. net gain or net loss) of ES value or possible new ES value from adapting or new ES.

## Results

### Global ES assessment

Total ES for the assessed area amounts to ~1.3 trillion international dollars. The highest valued areas are mostly centered in Europe, central United States,

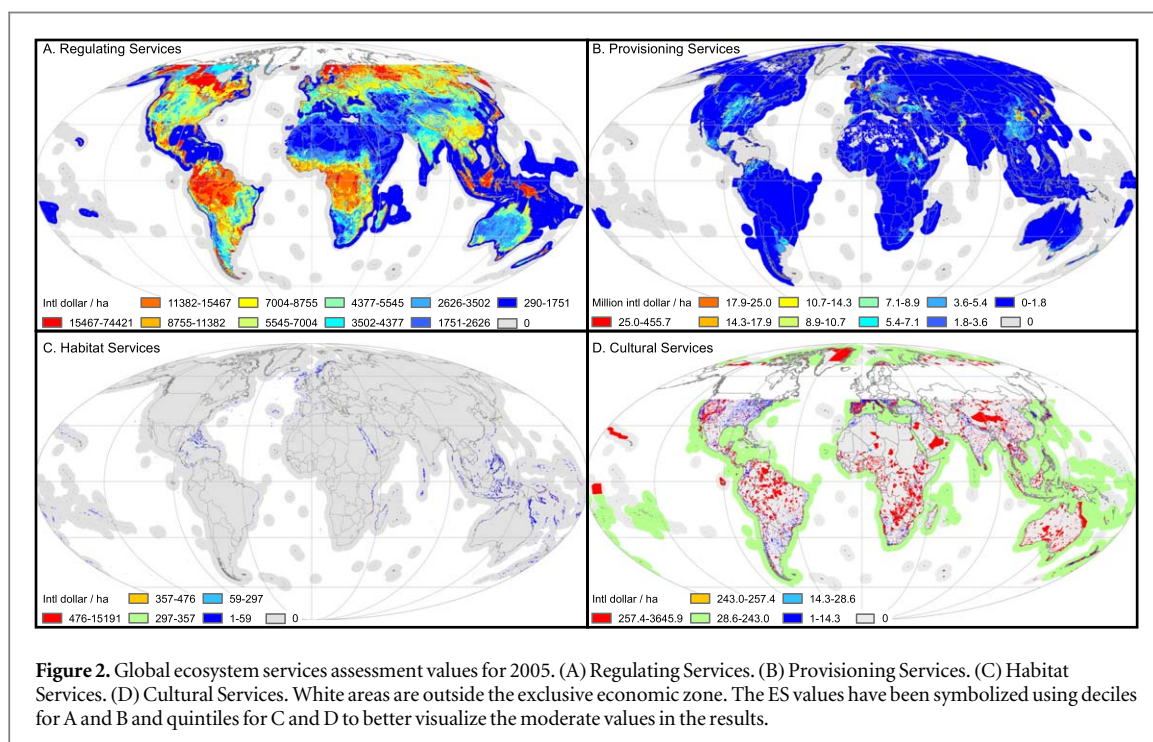
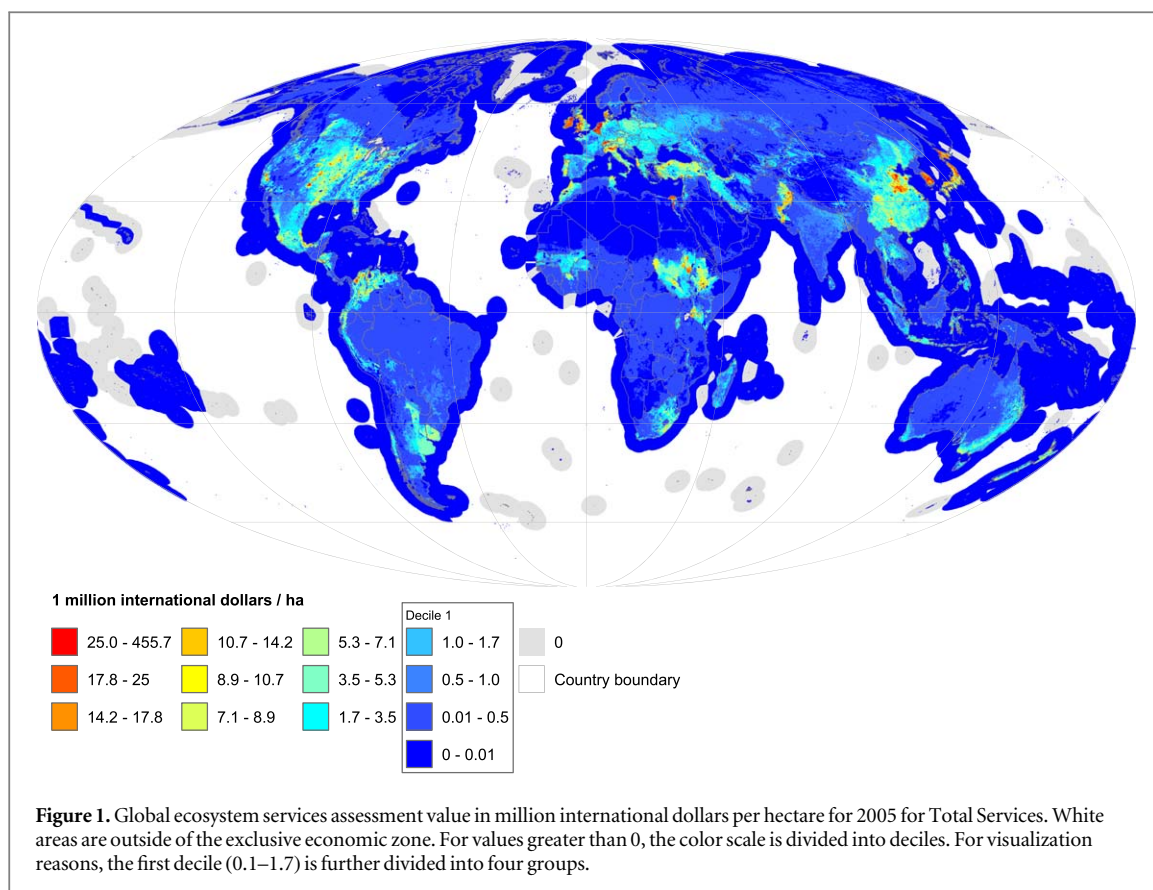
western Ecuador, northern New Zealand, and north-eastern China (figure 1). There are several localized areas of high value in several other countries.

Table 1, under the column 'Value (million international dollars)', summarizes the total values of each ecosystem subservice. The ES category mapped values are shown in figure 2. The Regulating services, which account for merely 0.8% of the total ES value, are highest valued in regions of dense forest (figure 2(A)). Provisioning Services account for 99.35% of total services, and highest valuations are concentrated in areas of high food production (figure 2(B)). Habitat Services are valued mostly along coastlines (figure 2(C)), and Cultural Services are widespread over valued areas (figure 2(D)). The latter two ES categories contribute minimally to the overall value of ES.

### Climate class transitions

Due to the consistency in downscaling and bias correction, we reduce the uncertainty in the model's historic simulations. This enables us to attribute all uncertainty for the future climate signal to the GCM's individual response to the RCP scenarios and not to initial biases in the model simulation. Using five GCMs per RCP scenario gave insight in the uncertainty of our projections of ES that will be in KGCC transitions. GFDL-EM2M is the only GCM shown for the KGCC transition (figure 3), because it exhibited more obvious spatial variation between 2005 and 2085 than the other four GCMs used in the study. For RCP 2.6, KGCC transitions from 2005 to 2085 reflect minor transitions in 16% of the locations (figure 3) (Wanders *et al* 2015). However, in RCP 8.5, KGCC transitions are more pronounced and occur in 34% of the world (figure 3) (Wanders *et al* 2015). The spatial variation in minor and major KGCC transitions are not necessarily the same for RCP 2.6 and 8.5. In some areas, the KGCC transition is the same, meaning both the minor and major class transitions matched (orange areas, figure 3); however, for 22% of the modeled area, there is a different KGCC transition, which may be for either or both minor and major transitions, between RCP 2.6 and RCP 8.5 (bright green, purple, and dark green areas, figure 3). The largest changes in climate types occur in temperate and polar regions due to expected increasing temperatures, decreasing precipitation, or changes in the precipitation regime. Regions typified as tropical, desert, and snow-dominated will increase in areal size because of increasing temperatures. Minor climate types show significant transitions within the same major climate type moving from colder to warmer. Existing literature has reported that climate changes are exacerbating drought impacts (e.g. Samaniego *et al* 2018, Van der Wiel *et al* 2019) and thus reducing water availability in large parts of the world. The transitions in KGCC also indicate that shifts in precipitation occur as a result of changes in temperature around the world. The GCM projections point

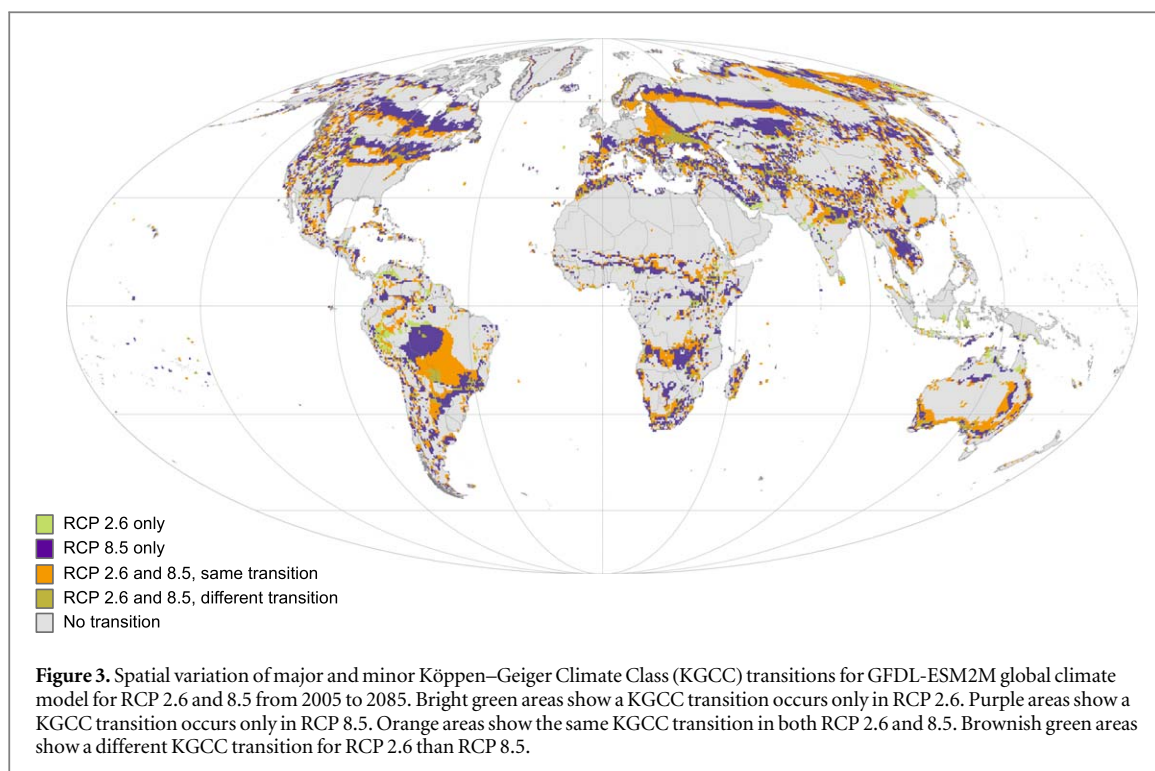




towards global changes in precipitation patterns and these are linked to the increasing temperatures.

The area in a KGCC transition increases over time regardless of the RCP scenario (figure 4—row 1). In RCP 2.6, ~17%–32% of the assessed area (figure 4—row 1, column 1) will transition into a new KGCC,

which is equivalent to between  $\sim 5 \times 10^7$  km<sup>2</sup> (roughly the surface area of Asia) and  $\sim 9 \times 10^7$  km<sup>2</sup>. By comparison, in RCP 8.5 and 2085, transitions into new KGCC will occur in ~33%–48% of the assessed area, which is about  $9.7 \times 10^7$  km<sup>2</sup>– $1.4 \times 10^8$  km<sup>2</sup> (figure 4—row 1, column 4). RCP 8.5 would affect at



the minimum a surface area equal to North and South America, Europe, and Asia combined to the maximum of an area equal to all continental land areas.

#### ES value in a KGCC transition

Figure 4 illustrates the temporal pattern of ES values in a KGCC transition. The RCP time series curves reflect the carbon emission scenarios from IPCC and projected KGCC transitions from the five GCMs. The total value of ES captured in a KGCC transition increases between 2000 and 2050, regardless of the RCP scenario. This means that as time progresses, more ES values are within a KGCC transition; whether or not this is an actual loss of ES is beyond the scope of this paper. There are no major differences between RCP scenarios until 2050. The ES in a KGCC transition for RCP 2.6 plateau (column 1), while RCP 4.5 (column 2) begin to stabilize at the end of the century (circa 2090). In RCP 6.0 (column 3) and RCP 8.5 (column 4), the percentage of ES value in a KGCC transition continues to increase in the same manner that the area in a KGCC transition increases. RCP 8.5 curves show greater and continued change at a greater rate (i.e. steeper slope) than RCP 6.0; RCP 8.5 total ES values change approximately 1.5 times faster than RCP 6.0.

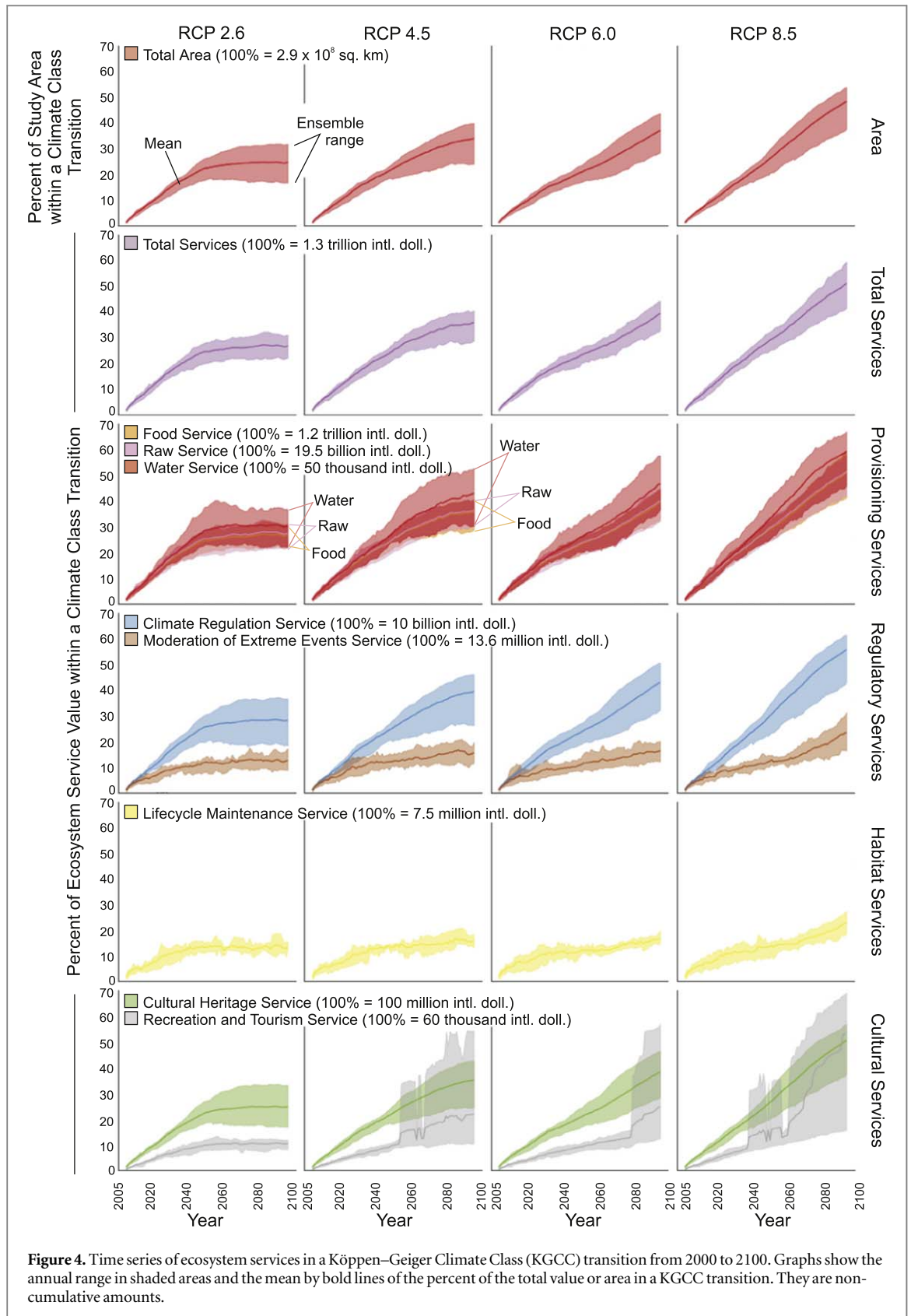
The total value of ES that ‘belongs’ to KGCC A increases from 2005 to 2085 (figure 5). This is shown by the increase in the vertical bars. The blue arrow between the two vertical bars for KGCC A shows that 25 billion international dollars changed minor classes within climate class A. The total ES value in KGCC A in 2085 has increased, because areas that were KGCC B or C in 2005 are now KGCC A in 2085 (indicated by

the orange to blue arrow and the green to blue arrow in figure 5). Transition matrices specifying the total ES value in specific KGCC transitions are available as part of the online data repository (<https://doi.org/10.5281/zenodo.3515435>). Polar climates (class E) have the smallest value change of 4.2 billion international dollars, which cannot be fully calculated because most polar regions are not included in economic zones (e.g.  $\sim 2.9 \times 10^6$  km<sup>2</sup> of the Arctic Ocean). The ES value originally associated with polar climates is now associated with other climate classes, such as continental. While a particular climate class has a specific loss of ES value, it does not necessarily mean the ES value has decreased.

Figure 6 illustrates the spatial pattern of where major and minor KGCC transitions (areas shown in pink and blue, respectively) will occur for RCP 2.6 from 2005 to 2085 for the four ES categories. Figure 6(B) shows the regions in all KGCC transitions for RCP 2.6 from 2005 to 2085 overlaid on the Provisioning Services spatial ES assessment. High value areas that are within KGCC transitions mainly center on the United States, Mexico, Colombia, Venezuela, Argentina, eastern Europe, Sudan, Ethiopia, Pakistan, and China.

#### Discussion

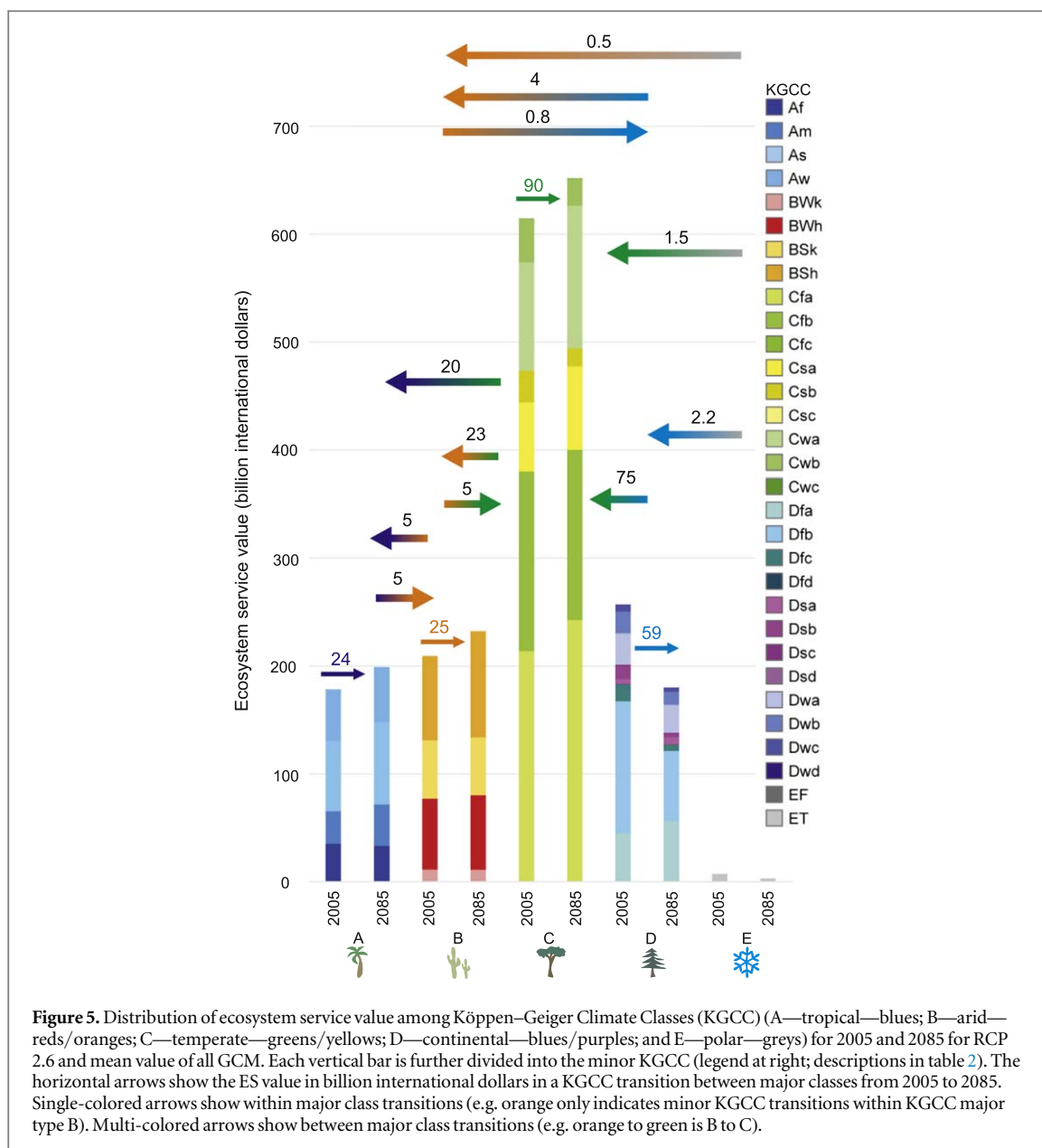
The results of this study showed the global distribution of ES in 2005, which are based on quantifiable input data and transparent methods. The subsequent overlay of the ES with CMIP5-derived climate classes determined how much of the ES value will be in a



**Figure 4.** Time series of ecosystem services in a Köppen–Geiger Climate Class (KGCC) transition from 2000 to 2100. Graphs show the annual range in shaded areas and the mean by bold lines of the percent of the total value or area in a KGCC transition. They are non-cumulative amounts.

KGCC transition as a function of time. The defining difference between this ES value estimation over different previous assessments (e.g. Boumans *et al* 2002, Sutton and Costanza 2002, de Groot *et al* 2010, Crossman *et al* 2013, Li and Fang 2014) is that value consistency was maintained by using production

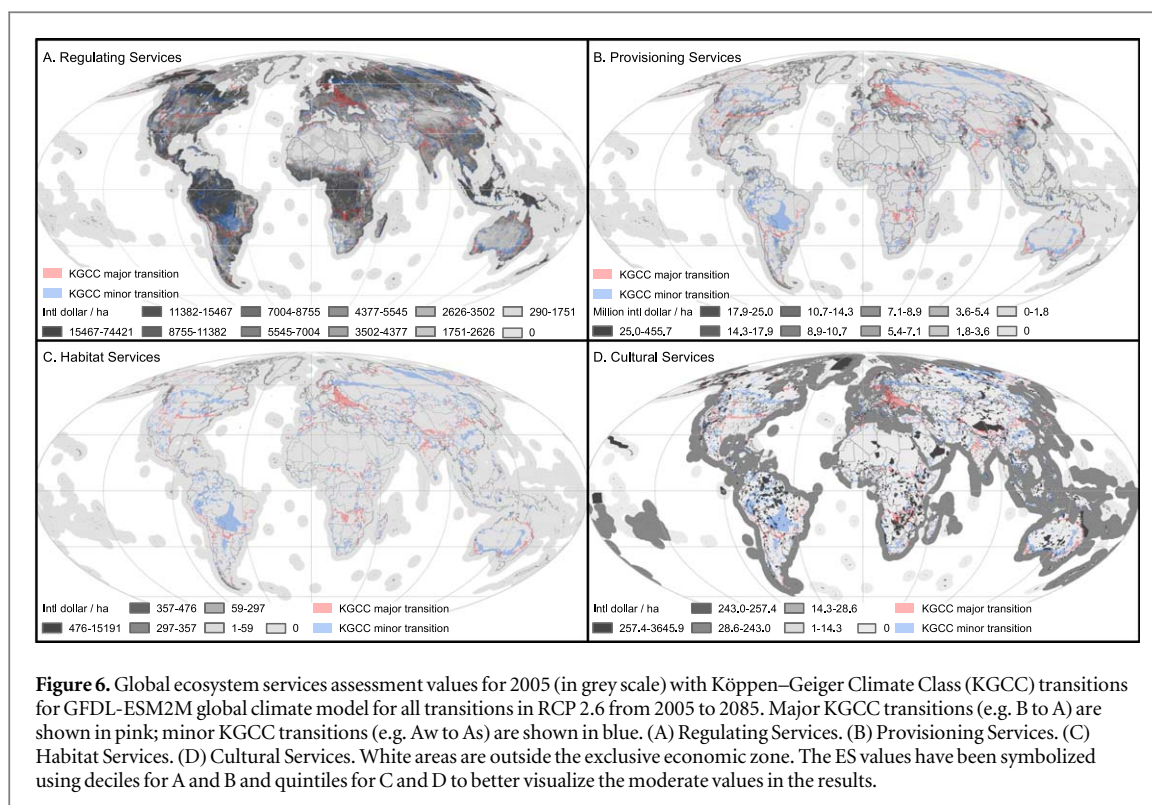
values and avoiding global values or estimations as much as possible. ES assessments use proxies to provide values for the services (Schägnier *et al* 2013), whereas this study uses production values as consistent and representative values of the services calculated. The global value of ES totaled ~1.3 trillion



international dollars. Of that value, 22%–31% (RCP 2.6) and 41%–60% (RCP 8.5) will be within a transition in KGCC.

Valuation by subservice can be calculated on a spatial basis providing clues for further work into climate change preparedness. Different regions are more prone to climate change effects because of the inability of some species to adapt quickly as concluded by IPBES (2019). KGCC transitions overlaid with the ES assessment maps may be used to help identify at-risk groups (e.g. Figure 6). By investigating these high-level maps, selection of at-risk-areas can be identified and more locally focused models can be produced. By making our data, including scripts, available (available at <https://doi.org/10.5281/zenodo.3515435>), the results can be used for further study of single or multiple subservices at the global or regional level. For more local scales, the models will need to be rerun with higher resolution input maps.

This ES assessment provided some interesting insight. The Food Service, under the Provisioning Services category, totals 1.2 trillion international dollars and accounts for 99.8% of the Provisioning Services ES value (figure 2(B), table 1). These findings are significant because they indicate that transitions between KGCC will greatly influence the Food Service; however, these results do not definitively indicate a future food shortage. The percent Food Service value in a KGCC transition greatly depends on the RCP scenario and temporal aspect (figure 4, row 3), but ranges between 22% and 60%. When looking at the Food Service subservices, the Livestock subservice is surprisingly high compared to the other subservices (table 1). This high value is due to the number of cattle around the globe and the high production value of cattle. This ES assessment includes all the cattle as a source of meat; however, it is overvalued because the number of cattle are not differentiated between dairy and meat.



The Water Supply Service, part of the Provisioning Services, accounts for only 0.1% of the total global ES value (table 1). Given the importance of water, the known shortages of water due to drought (Samaniego *et al* 2018, Van der Wiel *et al* 2019), and the lack of access to clean water globally, this service appears to be undervalued. The Water Service value, however, maintains a relative value to the Food Service in that the valuation method is the same (i.e. disaggregated production values). The Food Service has nine sub-services, whereas the Water Service has only two, Industrial Use and Drinking Water. Water prices were not available for all countries, so a global average was used in some cases. Additionally, the Irrigation Water subservice was not calculated separately because the FAO database provides farm-gate values which include all production costs, including water usage (supplemental information 1, supplemental information 2) (FAO 2015). Thus, including the Irrigation Water subservice separately would overvalue the ES assessment total because it is already accounted for in the Food Service. There is not enough information to extract the Irrigation Water subservice from the Food Service value to present the values separately. Supplemental information 1 and supplemental information 2 further explain the exclusion of the Irrigation Water subservice, among others.

The value of the Climate Regulation Service (10 billion international dollars) represents nearly 99% of the Regulating Services category value, but only 0.1% of the total global value (figure 2, table 1). High values for climate regulation correspond to tropical forests (e.g. the Amazon), where the carbon stock (i.e. Tier 1

biomass) is high, and higher latitudes (e.g. northern Canada), where the soil carbon is high (Ruesch and Gibbs, 2008, Hiederer and Köchy 2011). The high values reflect the high cost to society if the carbon were to be released due to deforestation or land cover change. Carbon prices are obtainable from various sources (e.g. Tol 2009, van der Ploeg and de Groot 2010) and vary widely depending on the kind of valuation method. When calculating the value of carbon, the social value of carbon should be used because this is the expected damage value if the carbon is released; additionally, market prices relate to carbon sequestration and not carbon storage (Natural Capital Project 2016). The Climate Regulation Service value calculated in this study is conservative, because the mode of all prices from a weighted, fitted distribution of social costs of carbon values, 41 international dollars per ton of carbon, was applied in the calculation; whereas the mean is 151 international dollars per ton of carbon (Tol 2009).

We identify a number of limitations in the modeling framework, which are recommended additions for future studies as well. First, ES assessments are anthropocentric by design and do not include benefits to other species of animals or plants, unless those benefits coincide with those for humans. Therefore, there is bias in the evaluation of ESs in general (Schröter *et al* 2014, Silvertown 2015). When using ES assessment results for decision-making, this bias should be taken into account.

Second, the GCMs used in the modeling are limited to onshore areas. Therefore, our ES values in KGCC transitions cannot include the offshore areas

because marine climate models are not included in GCMs. Figures 3–6 only present the baseline of expected change.

Third, the results indicate that there is an economic impact resulting from climate change and the human-derived benefits may shift either positively or negatively. We do not assess the possible new economies from adaptation to new climate classes. Therefore, we can only say where and how much of the ES value will be in a KGCC transition. The results from IPBES (2019), however, indicate that climate change is occurring at a pace faster than species are able to adapt locally. Therefore, managed plans need to be initiated.

Fourth, the scope of this study was limited to flagging the areas of ES in a KGCC transition for which we assumed that adaptations are required. A climate-based land-use model could potentially fill this gap, but it is currently not available at a global scale. This would enable the determination of a transition in climate class as beneficial to an area or not.

Within the ES assessment itself, there are three main sources of uncertainty. First, uncertainties originate from the published data sets, which may or may not be described. For example, the FAOStat database (FAO 2015) explicitly categorizes the values by year and by country noting how the value was obtained or ascertained. However, not all databases provide such information. Secondly, our modelling choices could use false assumptions regarding disaggregation based on land cover/land use (Nachtergaele and Petri, 2008), and our modelling does not include land change scenarios. For example, the Game subservice is assumed to refer to game acquired from hunting wild animals and birds and is limited to non-protected forests and grasslands. However, not all of the area may be appropriate or legal for hunting purposes. Thus, it is likely there are some areas valued for Game subservice that should not be included. Thirdly, constants, such as animal weights that are used in the Wool Fiber and Hide Fiber subservices and use one value for each animal type (e.g. sheep, cow), do not represent the global spatial variation of species differences (e.g. sheep species in New Zealand and Norway are not the same). Table 1 includes possible sources of error and supplemental information 1 describes uncertainty in the ES assessment in more detail.

With few exceptions (Costanza *et al* 1997, Li and Fang 2014, Millennium Ecosystem Assessment 2003), the results of previous ES assessments are not provided spatially. This study calculated the ES values in a spatial environment. However, the results themselves do not yet provide a complete quantitative valuation because not all ES in the assessment could be calculated due to lack of information to spatially quantify the ES. The total number of compatible services is 77, of which the ES assessment here accounts for ~40% of the services (some of which are combined services noted in Supplemental Information 2). All of the subservice and services inventoried are assessed in detail

in Supplemental Information 1 as to whether (1) inclusion in the assessment was conceptually compatible, (2) a calculation was possible, and (3) the data was available for a calculation. By making an estimate of the total value of the services missing data in this study but valued in previous studies (Costanza *et al* 2014; de Groot *et al* 2012) (i.e. 36 services), this ES assessment is estimated to be undervalued by 20%–22% or approximately 275–287 billion international dollars. Not all ES subservices quantified here provide all possible aspects for quantification. For example, Habitat Services quantify only coral and turtle nesting sites.

## Conclusions

This paper addressed the need for a transparent and spatially explicit ES assessment in order to evaluate the proportion of ES value in a climate class transition and has proposed a methodology with quantitative analysis. This analysis is important because of the known and imminent climate change that is and will affect ecosystems; this is recently documented and assessed by the upcoming report from IPBES (2019). Our main result shows that anywhere between 22% and 50% of global ES values, depending on the RCP scenario, will be in a KGCC transition. Results from the analysis can be used by local or federal governments to enact or change mitigation or management techniques for those ES in a KGCC transition. For example, by identifying regions where a climate class transition takes place, a government could assess whether current agricultural activities can continue (i.e. can a specific plant species survive in the new climate class?).

The global ES map is indispensable to create ES values by biome, country, continent, or at-risk areas for different hazards beyond climate class transition (e.g. earthquakes, landslides, rising sea level). These valuation maps can assist in decision-making.

Given the current pledges, it is unsure if we will meet the Paris Agreement RCP 2.6 emission scenarios; governments, researchers, and the public alike should brace for more transitions in KGCC and ES values over the next ~30 years, which is 2050 the major departure point in similarities between the RCP scenarios. If RCP 8.5 emission scenarios become the reality, the change will continue until 2099 and beyond. In order to better prepare for such changes, a better understanding of the local transitions is needed. Future research may incorporate more spatial data either by further refining calculated ES or by valuing the incalculable ES. Modeling possible new ES in predicted KGCC areas and incorporating uncertainty into the ES assessment are valuable future directions of investigation and those results will better assist in decision-making.

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## Data availability

The data that support the findings of this study are openly available at <https://doi.org/10.5281/zenodo.3515435>.

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