Advanced Review

Climate change and ecosystem services

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Studies of the impacts of climate change cover three broad areas: direct effects on humans, their enterprises, and assets; effects on natural systems; and effects on humans via natural systems. 'Ecosystem services' fall into the latter category. Future climates continue to allow ecosystem services to be delivered and consumed, in some cases at a level greater than in the past, and in others degraded relative to their historic supply. Across a wide range of ecosystem services, the losses exceed the gains for magnitudes and rates of climate change projected under low-mitigation scenarios. On balance, global mean temperature (GMT) rises greater than 2°C above preindustrial have a spatially patchy but net negative effect on many ecosystem services. The negative impacts occur in many places and affect most people. This apparent asymmetry of impact is hypothesized to have three causes: the rapidity of climate change relative to adaptive processes in social and ecological systems; the exposure of societies to climates not experienced during the period over which complex, agriculturally dependent human societies developed; and the approach toward limits in the Earth system. Covariates of climate change—especially rising atmospheric carbon dioxide and ongoing land transformation—are an inextricable part of the projected loss of services in the coming century and the projected shortfall between supply and demand is strongly demand-driven. The geographical distributions of ecosystem service supply and demand are unequal, and becoming more so.

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INTRODUCTION

The term 'ecosystem services,' defined as the benefits which people derive from ecosystems, was popularized in the 1990s,[1] though the general concept is much older. The most widely used classification of ecosystem services is that by the Millennium Ecosystem Assessment.[2] It groups the services into four clusters: 'provisioning services' (physical goods, usually with markets, such as food, fiber, and water); 'cultural services' (less tangible services, such as recreation or attractive landscapes, but nevertheless often directly or indirectly associated with markets, and some like spiritual values or sense-of-place which are deeply valued, but seldom monetarized); 'regulating services' (services which ensure the smooth and reliable operation of the ecosystem, or sometimes suppress 'dis-benefits' such as floods or pest outbreaks); and 'supporting services' (ecosystem functions not directly used by people, and therefore hard to associate with a value, but essential to the delivery of other services: photosynthesis, nutrient cycling and soil fertility are examples). This review will not deal

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with supporting services, because the benefits arising from them are mostly realized through the provisioning, cultural and regulating services, and to treat them separately risks double-accounting.

The position of biodiversity in this scheme is still a source of disagreement.[3] Only in special cases is the service derived from biodiversity based on the presence of *variety*, as opposed to being supplied by a small subset of individual species. The services delivered by individual species are most logically considered as provisioning services or in some cases regulating services (e.g., pollination by the honeybee, *Apis mellifera*) or cultural services (e.g., sacred or iconic species). To call this 'biodiversity' is a rather trivial use of the term. Diversity in the sense of biological variation is unquestionably fundamental for the generation of some regulating and cultural services,[4] so perhaps in these cases biodiversity could be viewed as one of the supporting services.

Ecosystem services arise at the intersection between social and ecological systems. Therefore, ecosystem services are neither biophysical nor social, but jointly defined. This raises some conceptual issues pertinent to projections of ecosystem services into the future, such as: 'does a service exist if it is not used?' In practice, it is useful to distinguish between the ecosystem processes responsible for the *supply*; the *service* as it is used by people, and the *benefits* that accrue thereby.[5–8] As both ecosystems and societies change over time, so does the spectrum of services. For instance, the ecosystem service of forage provision for draught animals is much less important in the 21st century than it was in the 19th century, now that few of us depend on horses for transport, even if the intrinsic capacity to provide forage may not have changed. When demand exceeds supply (typically the case) there is no conceptual problem, since the service will in the long term be restricted to supply. In this review, I generally contrast the supply and the demand for the service in order to identify potential shortfalls.

It has been widely noted that certain categories of ecosystem service often co-vary positively (even synergistically) with one another, while others co-vary negatively (i.e., they tend to be in competition). This has led to the idea of ecosystem service 'bundles.'[9,10] The phenomenon of ecosystem service bundles has several possible causes: it may be because the co-delivered services originate from a shared underlying condition, which is not substantially altered by the enjoyment of the benefit. Antagonistic services, however, may require different conditions, or their production may modify the environmental basis for the delivery of other services.[11] The great increases in the provisioning services of food and fiber in the modern world have frequently come at the expense of services such as water quality and landscape amenity.[12]

When exploring the effects of climate change on ecosystems services, it is necessary to disentangle supply-side effects from demand-side effects; the direct effects from indirect effects resulting from changes in underlying conditions; and effects of climate itself from effects of the many other dimensions of global change which accompany climate change (such as rising CO_2, land use change, air and water pollution, intensifying natural resource use, and loss of biodiversity). In the latter case, these covariates of climate change are sometimes causes and sometimes consequences of climate change. In other cases, climate and ecosystem service supply share a sensitivity to changes in underlying drivers, such as population and consumption growth. It is also necessary to consider the effects on ecosystem services of actions taken to adapt to or mitigate climate change.

There have been many recent reviews of the effects of climate change on particular ecosystem services or classes of services, such as food, forests, or water. This review does not set out to repeat those, but to act as a meta-meta-analysis. It asks 'what overall trends and patterns may be emerging, across and between ecosystem services, in response to climate change?'

PROVISIONING SERVICES

The absolute level of consumption of provisioning services globally is higher now than at any time in human history, due to growth in per capita demand and the size of the human population.[13] Nevertheless, chronic shortfalls are apparent in many regions; and within regions, in sectors of society with limited access to services. The demand for provisioning services is projected to continue to grow during at least the first half of the 21st century, as the population rises from around 7 billion in 2010 to a projected 10 billion in 2050, at which point it may be nearly stabilized, for the first time since the Neolithic Revolution.[14] This represents a 43% increase in population, but most authorities consider the increase in demand for provisioning services to be 70–100% (i.e., up to a doubling of current demand), with the difference being due to increase in per capita resource use as people become generally better off.[15,16] The area expansion of agriculture (including biofuel crops and plantation forestry) and its increasing use of inputs such as water, nutrients, and pesticides, is a major driver of generally negative changes in other ecosystem services.

Food Provision

The effects of climate on the ecosystem service of 'food provision,' and vice versa, have been the subject of many studies and reviews, so this section is longer than others. The briefest summary, for those not seeking details, is as follows: Climate change has spatially and temporally patchy effects on food provision, becoming generally negative for higher warming. Thus, for modest climate change (1–2°C rise in global mean temperature relative to preindustrial) *global* food provision is little affected, though food supply in many regions is already negatively affected, at 1°C. Above 2°C, the net effect becomes increasingly negative; and taking into account the rising demand for food and competition with other land and water uses (specifically, bioenergy production as a climate mitigation strategy), the risks to global and local food security from this level of climate change are high (the details follow).

Food provision is ultimately about human food security (the availability of sufficient safe, nutritious food, to all, at all times, to paraphrase the World Food Summit of 1996) rather than food production alone. The key issues in food security often relate to affordability, access, and dietary preference rather than the capacity of the highly specialized food-production ecosystems we call agriculture to deliver sufficient calories, proteins, and nutrients to meet the aggregate human need. Food, as a whole, is a non-substitutable good, but within that broad category there is great scope for substitution of one food type by another, with important ecosystem and cultural consequences. For instance, many studies[17] conclude that a 'Western' diet (high in grain-fed animal protein and high-trophic level fish) cannot be extended to all the future global population without substantial expansion of the planted area and an unprecedented transformation in crop productivity and water use efficiency. The expansion of the area occupied by croplands ('extensification') and the increase in yield per unit area ('intensification'[18]) needed to ensure global food security if everyone consumed this aspirational diet would result in major losses of other ecosystem services, notably those which depend on uncultivated land and uncontaminated water. History demonstrates that when faced with a tradeoff between food security and other ecosystem services, the imperatives of hunger tend to override all other considerations.

If, however, the diet is assumed to be nutritionally balanced and calorifically adequate but mostly based on vegetables, and food distribution is assumed to be efficient, several global studies conclude that food security is possible worldwide, even under modest levels of climate change (less than 2°C GMT rise relative to the preindustrial mean, with the latter typically proxied by the 1850–1900 temperature) and with a global population reaching around 10 billion.[15,16,19,20] This scenario would further require substantial reductions of waste in the food production system. It is not achievable without both expansion of agricultural area and intensification of agricultural management (i.e., increases in per unit land area inputs and outputs—including unintended leakage of nutrients, salts, sediments, and pesticides). 'Organic agriculture' as currently narrowly defined to use no synthetic fertilizers or pesticides and aiming to have a reduced impact on biodiversity and ecosystem services, is unlikely deliver global food security, given an average yield reduction of about 20% relative to conventional agriculture,[21–23] though at least one study suggests it could, if done right.[24]

Crop Agriculture

Crop agriculture has been a major focus of climate impact studies[20] (and the many studies cited therein, as well as Refs 25–28). Broadly speaking, the studies find that despite the modest fertilization effect of rising CO_2 (partly offset by simultaneously rising tropospheric ozone), locations of staple cereal and pulse production that are already hot during the growing season (i.e., daytime temperatures above the growth optimum for plants of 26–30°C, and temperatures during the critical flowering and seed-set period exceeding 30°C) experience yield declines under further warming, all else being equal. Places already dry—notably the subtropical semi-arid zones—are more likely to become drier than wetter in a warmer world, and are therefore likely to exhibit additional yield declines as a result. For those regions historically substantially cooler than the growth optimum for cereal yield and where moisture is currently comfortably adequate, yield increases are likely under a moderately warmer, wetter climate.

Even at the relatively modest levels of warming experienced by 2015, local inability to meet food demand is apparent. It is very likely to increase in future, especially in the dry tropics. The risk of global food crises increases due to a combination of demand- and supply-side factors, some of which are directly linked to climate: such as greater interannual climate variability (droughts and heatwaves especially); the possibility of coincidental crop failures within the small number of global 'breadbaskets' which produce the bulk of staple crops worldwide; and the risk of damage to food-sector infrastructure from severe storms.[29] For global mean warming above 2°C relative to 1960–1990, most global studies indicate a net decrease in food production, because yield declines become apparent in temperate as well as tropical areas.[20,28] The amount of yield loss rises in an accelerating fashion with further warming, even when reasonable adaptive actions are taken.[20] As the global scope for crop land expansion is now quite limited, the key adaptation to satisfy the projected doubling of food demand to mid-21st century is likely to be increased production per unit cultivated land and improved food system efficiencies, in both cases while trying to minimize the emissions of greenhouse gases from agriculture.[30] The estimated rate of productivity increase required is at the upper limit of what has been possible in the past, around 2% per year.[31]

Livestock and Dairy

A large part of the global agricultural landscape is given over to the needs of domesticated livestock, including poultry and farmed fish, either directly as grazing lands, or for crops destined for animal consumption. As a result, of the quarter of global plant production that is appropriated for human use (Human Appropriation of Net Primary Production—HANPP), a fifth to a quarter is consumed by domesticated species.[32] The redirection of this fraction to direct human consumption is one of the strategies to make food security possible for a larger human population in the future. On the other hand, a large part of the grazing landscape devoted to animal production is located in places where the land is too dry, or the soils unsuitable, for crop agriculture. In these places, reducing animal production decreases, rather than increases human food security, and leads to livelihood losses.

Dairy and meat production based on ruminant species generates about a quarter of global human-related methane emissions.[33] Emissions from enteric fermentation and animal wastes are mitigatable to a degree, but under current technology, not completely eliminated. As in the preindustrial era, rangelands usually supported large herds of wild ruminants, it is not a given that there has been a net increase of methane emissions following the replacement of wild ruminants by domesticated grazers.

Although the impacts of climate change on animal feed production are similar to those outlined for crops above, animal-based production has a further temperature sensitivity: warm-blooded animals have a genetically inflexible body temperature, all within a narrow range.[34] As the ambient temperature approaches the body temperature, animal productivity (and especially milk production) falls off steeply.[35] The extensive rangelands of the world, where livelihoods and cultures are often closely linked to pastoralism, are often already quite close to this limit for all or part of the year, and many are projected to become both warmer and drier in future[36] (but see a critique[37]).

Wild Fisheries

Overall, ocean primary production is projected to increase modestly under a +2°C GMT increase, but the response of fish production is complicated by marine biome shifts, changes in body size, and the as-yet poorly understood effects of ocean acidification on fish production.[38] Projections of ocean temperature changes suggest substantial geographical shifts in the locations of the broad types of marine fisheries during the 21st century as a result of climate change, but not necessarily a decrease in their total productivity (bearing in mind that the productivity of ocean fisheries is already under severe threat due to overfishing). Broadly, fisheries in tropical, temperate waters and Antarctic waters are projected to decline 40–60%, while northern high latitude fisheries are projected to increase 30–70%.[39–42]

Ocean acidification is an unavoidable consequence of rising CO_2 levels with many direct and indirect impacts on wild-caught fisheries, predominantly negative. Recent reviews[43,44] are available for this large, emerging field. Marine organisms which build their shells from calcium carbonate (in particular, the aragonite form of $CaCO_3$) are severely negatively affected as the ocean pH falls toward and below 7.8 (a level which will be reached by end 21st century under 'business-as-usual' emission scenarios such as RCP 8.5). Affected organisms include wild-harvested and farmed molluscs and crustaceae, but also the many planktonic organisms on which the oceanic food web is based. Even marine organisms with an internal skeleton (such as fish) are susceptible.

Coral reefs are highly vulnerable to the combination of warming waters, eutrophication resulting from runoff from the land, and ocean acidification.[45] The many species directly dependent on the coral reef habitat are threatened, along with the fisheries and tourism services it supports. Other services—such as coastal protection against severe storms—are indirectly threatened though weakening of the capacity of coral reefs to stabilize coastlines and shield them from wave energy.

The Products of Trees and Forests

Increased tree mortality has been observed in many places around the world over the past half century, in some cases to the degree that it is reasonable to talk of forest dieback.[46] There are many proximal causes of accelerated tree death, often acting in synergy: outbreaks of existing or novel diseases and pests; droughts and heatwaves; wildfires and storm damage. Ecologically, this pattern (syndrome) is what would be expected when a complex biome, like a forest, is subject to climate change. The naive perception of biome responses to a steadily changing climate is that the biome advances gradually and steadily at its leading edge, and retreats in an orderly fashion at the rear, where it is replaced by the next-biome-in-line. The reality is that the movement of a biome, when it involves many co-dependent, long-lived species, is manifest through an increasing frequency of disturbances (localized 'catastrophes'), leading to abrupt, messy and discontinuous community reorganization and possibly novel ecosystems.

Timber and Pulp

The growing human needs for timber as a construction material, industrial feedstock, or source of paper are increasingly satisfied by plantation forests dedicated to this purpose, akin to long-lived crops. Currently, more than half of global timber products derive from plantation forests, despite them occupying only about 4% of the global land area. The fraction of wood provided from plantations is projected to rise to three-quarters by mid-century.[47] Plantation forests are generally less productive of nontimber ecosystem services (e.g., water, biodiversity habitat, medicinal, and food plants) than more natural forests, but nonetheless supply a meaningful quantity of such services, and can be managed to supply more. Intensively managed plantation forests are a well-accepted part of many cultural landscapes. Plantation forests production rates per unit area have mostly increased during the last decades but the place-to-place variability is large,[46] as it is in future projections.[47,48] Projections for a 2°C increase of GMT suggest that the global supply of timber and pulp, largely from plantation forests, will continue to be adequate, partly due to management improvements and partly due to rising CO_2 and more favorable climates; but note caveats regarding the failure of the models to adequately represent some key processes such as rising CO_2 and altered disturbance regimes.[49]

Those studies that fail to consider the simultaneous increase in demand for the limited land, water, and biomass resources which underpin bioenergy, climate, food, and fiber services will overestimate the future capacity for the delivery of any one of them.

Biomass-Based Energy

A large fraction of the developing world still depends on wood or charcoal as a primary energy supply, and the fraction of biomass energy in the supply mix of both developing and developed countries is increasing due to its climate benefits.[50] Stringent climate mitigation scenarios, such as RCP2.6 and to a lesser degree RCP4.0, have a high dependency on Biomass Energy with Carbon Capture and Storage (BECCS)[51,52]. Much of this biomass is expected to come from forests (broadly defined), or from woody plants grown in short rotations on agricultural land. Some analyses suggest that RCP2.6 is not reachable without unacceptable tradeoffs with food production and biodiversity conservation. There are also often-ignored tradeoffs with the climate regulation service: bioenergy crops are not necessarily carbon neutral.[53] The core issue is that global net primary production functions under a number of quite stringent constraints, not easily alleviated at global scale without unacceptable consequences, and negatively affected by substantially higher GMT, despite the modest benefits from rising CO_2; furthermore, humans already appropriate a very large fraction of current production. Thus, diverting a much larger fraction of biomass to bioenergy[54] inevitably makes inroads into agriculture or into the currently semi-natural areas providing other ecosystem services, including biodiversity habitat.

Water for Domestic Use, Livestock, Growing Crops, and Industries

A dependable supply of water of a quality which is fit-for-use is an essential requirement for human and other life, but also for many 'secondary services' such as irrigated agriculture, urban sanitation, and power generation. There have been several global-scale studies and reviews of changes in the freshwater service in relation to climate change (a recent overview,[55] and specifically for groundwater[56,57]). The related but not identical issue of projected soil moisture drying trends in drylands[58,59] have been challenged on methodological grounds[37] on the basis that transpiration does not increase as steeply with rising temperature as simple physics would suggest when the CO_2 concentration rises simultaneously, because the latter results in decreases in stomatal conductance. The paleo-record does firmly support the contention that a warmer, higher CO_2 world is overall wetter, but this does not necessarily hold regionally, for instance, if precipitation decreases due to strengthened subtropical subsidence is the key driver of drying.

All studies agree that freshwater supplies are under pressure in many dry parts of the world, due mainly to rising demand. As a result of an interplay between changes in precipitation and evaporation, runoff is projected to decrease in most dry tropical regions and to increase in the wet tropics and at high latitudes. This leads to a mismatch between places with a rapidly increasing demand for water (the dry tropics), and places where the supply is increasing but demand is low or stable (wet tropics and temperate areas).

Most reviews conclude that global climate change exacerbates existing trends toward decreased water quality, for several reasons.[60] Warmer water encourages algal growth (already promoted by concomitant increases in nutrients) and pathogens. Disruptions of terrestrial ecosystems, due to biome movement and land use changes, lead to increasing sediment and nutrient loads. More extreme storms yield more sediment. More intensive water use leads to more polluted return-flows and less in-stream water to dilute them.

REGULATING SERVICES

Regulating services are the category believed to be most dependent on biological diversity and ecosystem integrity, and therefore most vulnerable to loss of diversity and the reorganization of communities as a result of climate change working in tandem with the many other causes of ecosystem disruption in the modern era.

Helping to Stabilize the Climate

The future behavior of the climate regulating service is particularly interesting in the context of climate change, because of the potential for converting the currently dominant negative feedback loops (stabilizing) into positive feedback loops (destabilizing). If ecosystems are relied on for future assistance on moderating climate change, then the climate sensitivity of the mechanisms of carbon storage in ecosystems is of crucial importance. Currently, land and marine ecosystems are together absorbing about half of the anthropogenic CO_2 emissions, helping to moderate the rate of climate change.[61] In the oceans, the equivalent service comes with considerable risk to fisheries and biodiversity-related services, as a result of the accompanying ocean acidification.[62] On land, the capacity to absorb CO_2 is limited and time-bound, because respiration or combustion of the stored carbon eventually balances or exceeds the uptake (for recent evidence, see Ref 63), and the respiration rate increases with temperature, while the uptake rate saturates with rising CO_2 and peaks and then declines with temperature. Furthermore, the incidence of wildfires has been observed to increase in some regions in recent decades,[64] and the fire risk is projected to increase under climate change.[65–67]

The fraction of anthropogenically emitted CO_2 remaining in the atmosphere is rising and is projected to continue to do so. Thus, although the absolute magnitude of the oceanic carbon sink and the terrestrial carbon sink continues to increase, their proportional contribution to the carbon budget is declining at a global scale.[61]

The avoidance of deforestation, through schemes such as Reduced Emissions from Degradation and Deforestation (REDD) has co-benefits for the maintenance of forests dependent ecosystem services (this is what is meant by the '+' in REDD+).[68] The climate regulating service of new afforestation is widely advocated as a mitigation activity. However, the net climate change mitigation benefits of planting new forests in previously nonforested environments is increasingly questioned, and the adverse tradeoffs in relation to other ecosystem services may limit this strategy.[69] For instance, where such forest plantations result in a darker land surface, the climate benefits of carbon uptake are considerably offset or even nullified. This is unimportant in mostly cloudy locations, because it is the cloud cover rather than the land surface that controls the albedo. Thus, afforestation in the tropics is typically a net climate benefit, whereas in subtropical, temperate, and boreal areas it may not be.[70,71] Where transpiration is increased as a result of afforestation, runoff is decreased.[72] Plantation monocultures replacing previously species-rich vegetation represent a severe tradeoff between climate regulation and biodiversity protection.[73]

Protecting against Storm and Flood Damage

Intact riparian and coastal vegetation have been widely shown to attenuate flooding and reduce bank and coast erosion.[74–77] This service is generally in decline worldwide due to coastal and riparian development, but is projected to be increasingly important in a future of more extreme storms and sea level rise. Many of the initial set of Ecosystem-based Adaptation (EbA) projects are founded on the principle of enhancing this service. Protected or restored natural communities are suggested to be a more cost-effective and resilient defense against rising sea levels and increasing storm severity resulting from climate change than the 'hard engineered' responses that dominated in the 20th century, though the evidence-base in support of this claim remains sparse.[78–80]

Keeping Pests and Diseases under Control

Over the past centuries, there has been a proliferation in the extent, frequency, and severity of outbreaks of often novel diseases of humans, their plant and animal domesticates, and wild organisms, despite great advances in treatment technology.[81] At the same time, there has been an increase in the spread of 'alien invasive species,' that is, species that become very successful outside of their historical area of distribution.[82] Many factors are involved in these changes: increased movement of people and goods, increased opportunity for trans-species disease transmission, larger and more densely packed human and livestock populations are among the explanations. In addition, there are plausible arguments that ecosystems are more vulnerable to the outbreak of single species populations, when they have reduced landscape and species diversity and are experiencing climate-induced stress. There is inferential evidence that scenarios of high climate change (which also typically represent futures where propagules move more easily by piggy-backing on trade and human movement) will be accompanied by further weakening of the ecosystem service of pest and disease suppression, which could then undermine the provision of other services.[83,84]

Pollination

Pollination is a biological mutualism essential for many specific instances of the food production ecosystem service. Pollination is also crucial to the integrity of natural ecosystems. There are global concerns regarding the widespread observation of declines in pollinator populations and diversity,[85,86] for which several causes have been mooted, including the use of insecticides, the proliferation of bee diseases due to the movement of hives by the beekeeping industry, and loss and fragmentation of pollinator habitat due to the increase in scale of modern agriculture.[87,88] As the pollinator and its target flower have the potential to respond differently to climatic cues and thus become decoupled, climate change is high among the concerns.[86,89–93] Observed changes in flowering phenology have been among the first biological markers unequivocally attributed to climate change (many references are cited in Ref 46). There are further potential negative impacts on the capacity to deliver pollination services (and the pest regulation services discussed above) resulting from changes in the structure (physical layout) and composition of the landscape, both of which are sensitive to climate change, among other drivers, especially if the change is rapid. Thus, the projections of the impact of climate change on the pollination service are generally pessimistic, though some commentators point to a high capacity for genetic adaptation in some pollinator species[94] as a reason to be somewhat less pessimistic in the longer term.

CULTURAL SERVICES

The highly valued, but hard to quantify cultural services—variously described as 'heritage,' 'sense of place,' 'identity,' and 'spiritual' services—are often based on patterns of landscape structure and composition, including the presence of particular species or features, which have co-developed with particular societies. Many of these will be climate-sensitive, but there is not an extensive formal ('scientific') literature dealing with climate risks to these cultural services. The possible vulnerability of these services is a concern more frequently raised by indigenous, traditional or local knowledge systems. Conversely, harnessing the power of cultural values has been invoked as an important strategy in adapting to climate change.[95,96]

Tourism and Recreation

In contrast, the cultural services of recreation and tourism support a large market, and there is a correspondingly large formal literature. Some recreational services are highly vulnerable to global warming in their current locations: notably outdoor winter sports,[97,98] and possibly tropical holidays in places which could become dangerously warm, stormy, or more prone to disease.[99] Those which are carbon-energy intensive (such as requiring travel to distant locations) are vulnerable to increases in the price of carbon-based energy.[100] Cultural landscapes are under threat everywhere from many stressors, including climate change: not because their elements could not be recreated elsewhere, but because they may no longer be viable where the people who created them live. An example is the advancement of the date of blossoming of cherry trees, an important cultural marker in Japan.[101]

WHY IS THE NET IMPACT OF CLIMATE CHANGE ON ECOSYSTEM SERVICES APPARENTLY NEGATIVE?

Based on the above survey of key provisioning, cultural, and regulating services, it appears that the impacts of climate change on ecosystem services are predominantly negative (Figure 1). The figure is the author's subjective interpretation based on the literature reviewed. The circles represent the net global outcomes at present an in the year 2050, and for the future date the bars indicate the range of regional outcomes. The impact on some services is suggested to be net neutral for modest levels of climate change (e.g., marine fisheries and plantation forestry). Only a few services are suggested to have absolute increases due to climate change (e.g., the volume of water supply, in some places).

There is no obvious *a priori* reason why climate change should have more negative than positive impacts on ecosystem services. Even should the climate change radically, ecosystems will continue to exist in future, albeit in highly modified form. Human societies are also likely to persist, given their demonstrable adaptability, and will continue to depend on ecosystems to supply various needs. Thus, ecosystem services will continue to be both supplied and demanded in future, though certainly in different forms, places, and amounts relative to the present. Therefore, is the dominance in the literature of negative over positive effects of climate change on ecosystem services real, or is it a reflection of some innate pessimistic bias among ecosystem service and climate change researchers? In the following section, I propose three hypotheses why a negative asymmetry in impacts may be real rather than imagined.

Hypothesis 1. *During the transition from one state to another, changes are likely to be disruptive even if the new equilibrium state, once reached, is as favorable or more so than the original state. The more rapid the transition, the larger the change, and the more heterogeneous the organism responses, the bigger the disruption.* The rate of climate change during the 21st century under a projection of current trends (the RCP8.5 scenario) is around 0.06°C/year,[46,102] more than 10 times faster than the average rate of climate change during the emergence from the last glacial period, though there may have been shorter periods within this transition (e.g., the Younger Dryas) when the rate of climate change was as fast.[103]

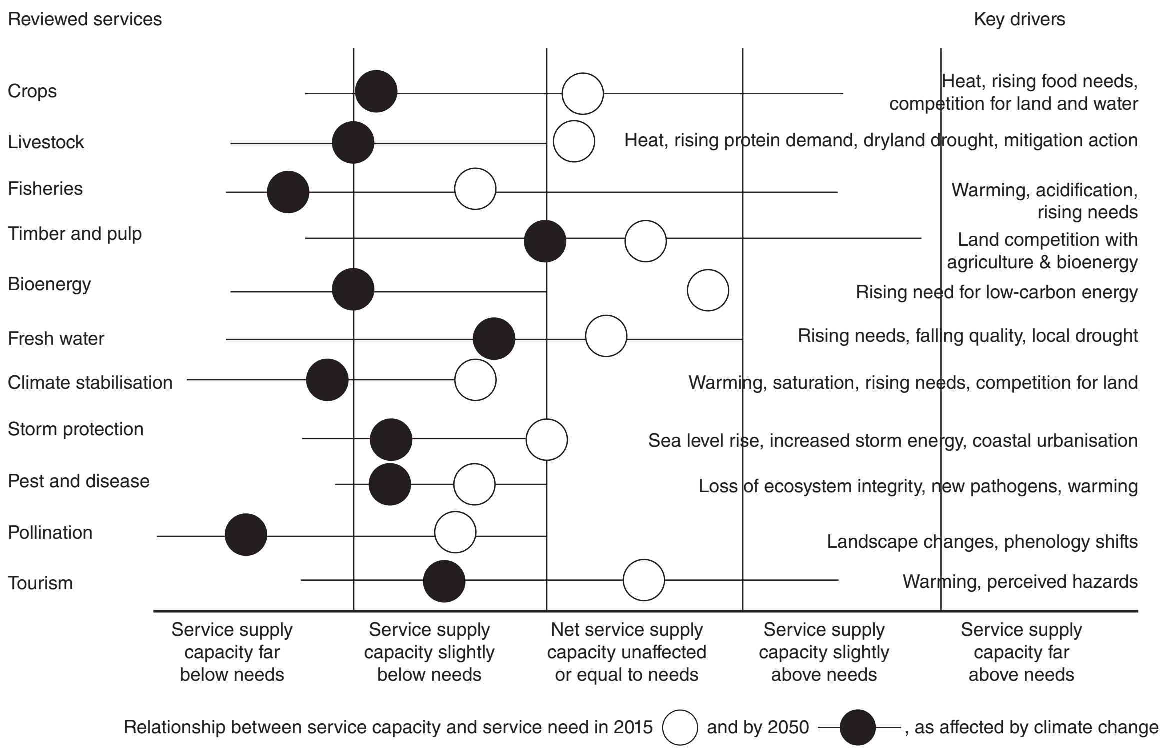

FIGURE 1 | A visual summary of the relationship between supply and demand for the ecosystem services surveyed in this review, both at the present time (open circles) and around mid-century (filled circles, with the range of local outcomes depicted with a bar). The qualitative assessment is by the author, informed by reading the studies reviewed.

If this hypothesis is true, adaptive strategies hinge on moderating the rate of change and assisting species and ecosystems to match it, through removal of dispersal barriers in the landscape and through active assemblage of communities.

Hypothesis 2. *The current human expectation of ecosystem services is hump-shaped with respect to climate, and climate change is shifting the Earth System toward the declining limb of the hump*. The climates which social–ecological systems are projected to experience in the mid-21st century under continued climate change are outside of the range in which they evolved during the Holocene (the past 12,000 years), and in some respects, the climates of the Pleistocene (approximately the past four million years). While the Pleistocene was characterized by periodic swings in CO_2 and climate between glacial and interglacial periods, our projected future is much higher in CO_2 and warmer than has been experienced during this period, a 'no-analog' circumstance which has led to the suggestion that a new Earth system regime, the 'Anthropocene' has been entered.[104] The Holocene was an unusually constant and stable climate period, during which settled agriculture and complex human societies evolved.[105]

The adaptive strategy in this case, after limiting climate change to the degree possible, is largely on the human side: change the spectrum of ecosystem services demanded by society, and the ecosystems from which they are derived.

Hypothesis 3. *It has been suggested that human use of the ecosystem services provided by the planet as a whole is approaching biological and physical limits.*[106,107] *If this is true, then it would be expected that ecosystem services would be truncated on the side of large-magnitude climate change, because it coincides with increases in other demands placed on the planet*. Obvious examples of limits being approached at global scale are the area of arable land and the supply of freshwater in dry parts of the world. These are not exclusively climate change-driven phenomena, but climate change is part of the syndrome of global changes that have created or are exacerbating the risk of the transgressing planetary limits for sustaining a complex, advanced civilization such as we now have. At a much more local and organismal scale, biological thresholds such as body temperature or the pH limit in marine ecosystems for calcium carbonate shell formation are also being approached in many places.

Under this hypothesis, the strong biophysical limits to ecosystem service capacity are not amenable to adjustment; therefore, adaptation must be based on decrease in consumption. Many responses emphasize efficiency gains: getting more useful service out of the constrained biophysical system for the same consumption. This runs the risk of decreasing resilience. A lower-risk strategy would aim at reducing absolute ecosystem service demands, combined with reducing the stress on ecosystem function from all sources, in order to back away from the limit.

All of these hypotheses call for an active strategy to adapt ecosystem service supply and use to a changing climate.[108]

CONCLUSIONS

The majority of the projected impacts of climate change on ecosystem services are negative. There is concern, worldwide, regarding current and projected declines in the absolute supply of a range of ecosystem services or a worsening of the relationship between the projected supply capacity and the projected future demand. Studies subsequent to the first systematic survey of global ecosystem services around the year 2000[12] have generally confirmed the pattern of weakening supply in relation to demand for ecosystem services related to freshwater, functional biodiversity and unique landscape features (typically cultural services) while the food, fiber and energy-provisioning services have grown in both supply and demand, often at the expense of the aforementioned services. Many factors are involved, including climate change and the actions taken to mitigate it. Nonclimate drivers include the growing demand for many services, underpinned by increases in the human population and especially the growth in per capita consumption of resources; the reduction in the physical area of many ecosystems critical to the supply of the services, poor management of the resource (e.g., by over-harvesting), concomitant loss of biodiversity, and overloading the ecosystems with chemicals which are either toxic or are beneficial in small amounts but disruptive in excess (such as nitrogen, phosphorus, sediment, and carbon dioxide). Climate change is widely projected to worsen these trends, as well as constraining the continued expansion of the food and fiber-based services which have flourished over the past century. A variety of mechanisms are involved, including the disruption of community relationships in ecosystems through mismatched phenological responses, movement in adaptation to climate shifts or disturbance regimes, and exceedance of apparently hard-wired limits such as the temperature-sensitivity of grain formation or the body temperature of mammals.

The impacts of climate change on ecosystem services are unevenly distributed around the world—with hotter, drier places and the polar regions more affected than temperate regions—and this spatial pattern is likely to intensify over the next century.[109] The most impacted areas broadly correspond to regions of low human welfare, rapidly growing populations, and low historical contribution to the causes of global climate change. Thus the impacts are inequitably distributed. The difference between the global aggregate impact and what is experienced locally is another potential source of inequity and conflict. For instance, the global need for services motivated by the need to mitigate climate change, such as bioenergy and carbon sequestration, may directly or indirectly conflict with rising local needs for food crops. Consumption per capita is higher in the developed than developing world for certain services (such as food and wood products) but the rate of growth in consumption is higher in developing countries, often in places with high climate change vulnerability.

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