



Assessing the potential risks of climate change on the natural capital of six countries resulting from global warming of 1.5 to 4 °C above pre-industrial levels

Jeff Price¹ · Rachel Warren¹ · Nicole Forstenhäuser¹ · Rhosanna Jenkins¹ · Erin Graham²

Received: 2 September 2020 / Accepted: 27 November 2023
© The Author(s) 2024

Abstract

We present the results from a new framework providing an assessment of how climate change risks to natural capital accrue with warming of 1.5–4 °C in six countries (China, Brazil, Egypt, Ethiopia, Ghana, and India). Unlike typical biodiversity and climate change studies, this assessment also considers landcover and population changes across a range of 17 ecosystem services. The potential impacts of climate change (alone) on natural capital at 1.5 °C is greatest in Brazil and least in Ghana. However, when population and landcover change are included, areas projected to be at high natural capital risk begin to accrue by 1.5 °C in all countries. By 2 °C, Ethiopia and Ghana show increasing areas at high risk, even though they are at low risk owing to climate alone. Thus, current impacts to biodiversity and ecosystem services and changes in potential demand coupled with warming exceed changes projected by climate alone. However, this also indicates that there is adaptation potential, especially with warming of < 2 °C, to reduce risk through restoring habitat. At lower levels of warming, targeted restoration of marginal agricultural habitats would increase the bank of natural capital for use by people and provide support for remaining agricultural lands. By 3 °C, the adaptation potential from restoration is substantially less: < 1% in Brazil, India and Egypt; 7–8% in China and Ethiopia; but still 26% in Ghana. This indicates that restoration as an adaptation option for biodiversity, and thus, natural capital, rapidly decreases with increasing temperatures. By 2100, factoring in population change (SSP2), current ecological footprint, and current landcover, even with only 1.5 °C warming, large parts of Brazil, eastern China, most of Egypt, much of Ethiopia, southwestern Ghana (except for protected areas), and most of India are at high to extreme natural capital risk with an adaptation deficit potentially equating to a soft adaptation limit.

Keywords Climate change · Risk · Natural capital · Ecosystem services

✉ Jeff Price
jeff.price@uea.ac.uk

¹ Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK

² James Cook University, Townsville, Australia

1 Introduction

This collection of articles in *Climatic Change* presents a harmonized assessment of projected climate change risks in six countries using a consistent set of climate change and socioeconomic scenarios. Here, we explore the implications of climate change to the ecosystem services provided by biodiversity, and thus to the natural capital of these countries. The literature is consistent in reporting that decreases in ecosystem services and natural capital are expected to be associated with climate change-induced biodiversity loss (e.g., Parmesan et al. 2022). However, there have been few published studies on natural capital using quantitative information including one global study on rangelands (Boone et al. 2018), and quantitative analyses for small areas within a country (Lovett et al. 2018). Most studies of the impact of climate change on biodiversity focuses solely on the climate part of the impacts (e.g., Warren et al. 2018) who found that nearly half of the insects and more than 40% of the plants studied were projected to lose more than half of their climatic range with $\sim 3^\circ$ of warming. Biodiversity, ecosystems, and ecosystem services are deteriorating worldwide, nature has been significantly altered, and most indicators of ecosystems and biodiversity are showing rapid decline with an accelerating global extinction risk (IPBES 2019). Since 1970, land use change has had the largest negative impact on nature (*op cit*). This study goes beyond modelling the impacts of climate change on biodiversity by quantifying the risk to natural capital by combining the potential impacts of climate change on biodiversity with an examination of current landcover patterns, and how these might be influenced by human population growth to 2100.

The six countries in this study were selected to span different levels of development, as well as different continents: Brazil, China, Egypt, Ethiopia, Ghana and India (exclusive of the disputed region with China and Pakistan). Risks were quantified for 1.5–4 °C warming above pre-industrial levels for the year 2100, comparing a case where human population remains constant at 2010 levels, and one where it evolves as in Shared Socioeconomic Pathway 2 (SSP2; Jones and O’Neill 2016). These levels of warming span the goal set in the UNFCCC Paris Agreement of limiting warming to well below 2 °C, as well as higher levels, e.g., 3 °C, consistent with current national policies under the UNFCCC in terms of countries’ nationally determined contributions (NDCs) (Rogelj et al. 2016). We provide estimates on natural capital risk using a new framework, WallaceNC, allowing us to examine the implications of changes in biodiversity to underlying ecosystem services and then on to the overall risk to natural capital. We draw upon the work presented elsewhere in this collection (Price et al. 2024) as well as the Wallace Initiative (WI) database underpinning Price et al. (2024), and fully described in Warren et al. (2018). This database examines the potential impacts of climate change on $\sim 130,000$ terrestrial species of fungi, plants, invertebrates, and vertebrates. Thus, using the WI database allows for a consistent approach across the biodiversity-driven ecosystem services examined. Seventeen different ecosystem services are assessed, 16 of them using changes in biodiversity (in whole or part) tied to these data with different services drawing from different combinations of taxa, as appropriate. One ecosystem service, food production, draws not from crop models but from projected changes in extreme events (e.g., drought (Price et al. 2022) and water logging).

Many studies have focused on assessing changes to ecosystem services resulting from landuse change in these countries (Leh et al. 2013; Tolessa et al. 2017; Song and Deng 2017; Liu et al. 2019; Talukdar et al. 2020), but few have included climate change. In the global scale study on rangelands mentioned above, significant reductions in ecosystem

services were projected across Ghana, while slight increases were projected for Egypt and Ethiopia, and China and Brazil showed a mixed response. There is limited research into natural capital and ecosystem services in Africa, and these either exclude the effects of climate change (e.g., Woldegerima et al. 2017) or provide a qualitative approach without quantification (e.g., Pettinotti et al. 2018). Some studies have quantified changes to natural capital and ecosystem services linked to observed climate change in China (Wang et al. 2016; Jiang et al. 2016; Fu et al. 2017; Tang et al. 2018), but have not considered the possible impacts of future climate change. In India, natural capital proxies have been used to estimate regional vulnerability to climate change (Brenkert and Malone 2005), but without quantifying potential changes to natural assets in the future. The only one of the six countries in this study with previous work quantifying the effects of climate change on ecosystem services is Brazil, where previous work has explored the risks posed by climate change to pollination (Giannini et al. 2012, 2013, 2017; Elias et al. 2017) and water-related services (Ferreira et al. 2019).

Ecosystem services are broken down in different broad categories of service (MA 2005). These broad categories (the services we examine listed in the parentheses) include provisioning (clean water, wood, food, and medicine (we separate crops from wild food/medicine), pollination); supporting (soil formation, seed dispersal, biodiversity, habitat); regulating (flood control, pest control, carbon uptake/storage, clean air, cool temperatures); and cultural (stewardship, recreation, aesthetics/existence value). There have been several papers examining the flows of biodiversity through to ecosystem services, and we base our selection of which taxa are associated with which ecosystem service primarily on these works (e.g., Mace et al. 2012; Balvanera et al. 2017, Lovett et al. 2018). Most species perform several 'jobs', i.e., support many different independent ecosystem services. For example, forests clean the air, sequester carbon, can reduce flooding, cool the air, and provide timber. Thus, the impacts of climate change to forests can also impact several different services. Natural capital is then framed in the context of the overall inventory and how it changes under different levels of warming. The overall projected potential risk is then presented as categories ranging from low to extreme in the absence of population growth with the addition of a category to express the need to import services if population grows to exceed the supporting capacity of the landscape.

2 Methods

The baseline for any study of ecosystem services and natural capital is biodiversity. The number of potential ecosystem services and their constituent parts varies from author to author, as does the way biodiversity is used in calculating these services. Here, we use lists of potential ecosystem services that feed into natural capital found in various publications (Mace et al. 2012, Lovett et al. 2018). The biodiversity metric used in this study is species richness change. The complete breakdown of the services, the development of the baseline, and the exceptions (stewardship, carbon and food) can be found in the SM. Each of the 17 ecosystem services were quantified using a simple scale having a minimum value of 0 (no service remaining) to 1 (full potential to provide the service). A sum of the 17 ecosystem service values was used to provide an overall estimate of natural capital NC in a spatially explicit fashion. The weightings reflect the landcover of the individual grid cell, excluding, partly including, or fully including it as appropriate (Table S1, SM). As the purpose of this study was to assess the risk to the six

study countries to loss of natural capital under climate change, then the analyses of each of ecosystem services take into consideration the potential impacts of climate change on biodiversity. However, risk goes beyond the climate risk and extends into past changes to the underlying base capability of an area of land to provide a service, and how these changes might increase (or decrease) in the future with population changes.

Biodiversity The biodiversity data used in this study were derived from the well-documented WI database (Price et al. 2024; Saunders et al. 2023; Parmesan et al. 2022; Warren et al. 2018). The individual species models are then aggregated into changes in species richness by taxonomic level (e.g., genera, family) and some specific taxonomic groupings (e.g., pollinators). More information on the methods, caveats, and potential limitations can be found in Warren et al. (2018). For this study, an additional step was undertaken to elevationally downscale the data from 20 to 1 km (Saunders et al. 2023).

Landcover Current anthropogenic impacts on the landscape were assessed using 2015 300-m resolution remote sensing data from European Space Agency (ESA) Climate Change Initiative (ESA 2017). This landcover dataset was used to assess the baseline likelihood of a given 300-m cell being able to support the biodiversity underpinning the ecosystem services. For example, the amount of biodiversity (as measured at the species level) in intensive agricultural systems is usually less than in surrounding natural areas. While croplands can play a role in localised flooding reduction, it is not a year-round benefit. Some ecosystem services, such as carbon uptake/storage, include all agricultural types. Others, such as stewardship, do not. However, food production, as distinct from wild food production, is only considered to occur on lands classified as agriculture or grassland. The biodiversity data was subsequently resampled to match the 300-m resolution of the landcover data (ArcGIS Pro Resample, nearest neighbour) to allow for analyses across the rasters. All results presented here are at a 300-m resolution.

Population Human population size, distribution and economic growth are all important drivers of global change, both historically and into the future. Thus, estimates of change—both in size and space—are important in understanding how human pressures and demand on natural resources will change in the future. Population data for 2010 (the closest data to match the 2015 land cover data and earliest projection available in the data used) and 2100 comes from downscaled 1-km spatial population scenarios (Jones and O'Neill 2016; Gao 2017). The SSPs describe alternate futures and are used in many climate change studies (O'Neill et al. 2017). SSP2, the pathway used for the studies in this project, is considered a 'Middle of the Road' pathway with trends not shifting substantially from current trajectories. Global population growth is moderate, levelling off in the second half of the century. Population growth impacts are both direct (e.g., land conversion to build settlements) and indirect (land conversion to grow food that is then distributed within the country). We treat the two equally based on published work on the potential impacts of urban growth on biodiversity (McDonald et al. 2020). In this study, we explore the implications of different combinations of climate change (and its regional implications) independently of local population change. This is because whilst climate change is partly driven by a global population change, it may be independent of local population changes in the country in question.

Ecosystem services The 17 ecosystem services examined (see SM for more detail) were *food, carbon, stewardship, wood, insect pest control, pollination, seed dispersal, soil*

production, wild food/medicine, overall biodiversity, nature-based recreation, aesthetic/existence value, cleaning the air, cleaning the water, cooling the air, flood control, and habitat. The underlying ‘weighting’ (0–1), based on expert judgement, used to determine the number of potential ecosystem services per different landcover type can be found in SM Table 1. These weighted values were then summed across the individual ecosystem services to generate a baseline of the potential ecosystem services in each cell in each country, out of 17 (Fig. 1). The sum of these ecosystem services makes up a natural capital baseline used in an examination of how potential climate change impacts on biodiversity could lead to increasing risks to natural capital. As would be expected, natural areas support more ecosystem services than agricultural areas. A different way of looking at this is that natural areas form the ‘bank’ of services that supports the growth of food in agricultural areas.

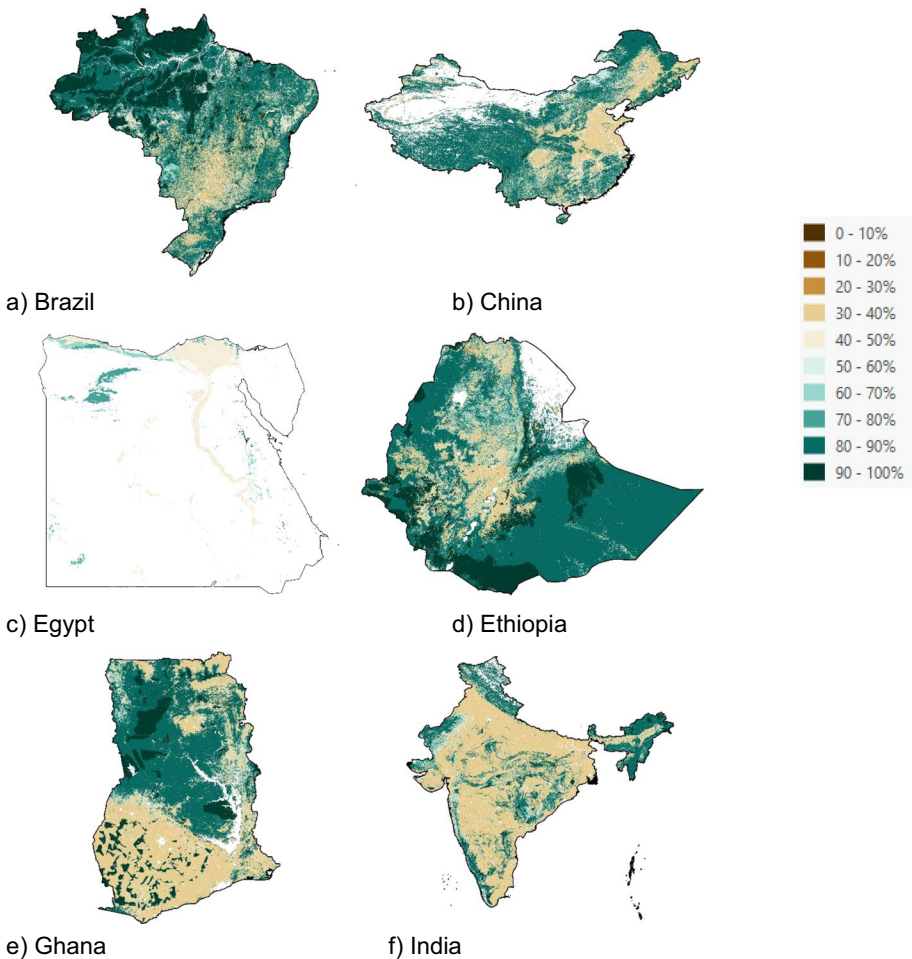


Fig. 1 Percent of ecosystem services (17) present in each cell of each country provided as a percentage as some ecosystem services (e.g., carbon) are not ‘fully’ present in each cell. Green areas have more natural land cover, brown more agricultural and white areas, no data (see below)

2.1 From natural capital to natural capital risk

The summing of the ecosystem services into natural capital represents the ways changes in the inventory/stock of biodiversity can potentially impact the overall amount of available capital. However, demand must also be considered. ‘Current’ demand is taken as the changes that have already occurred over time leading to the landcover distribution in 2015. These changes are known to have already impacted biodiversity (IPBES 2019; McDonald et al. 2020). To capture potential future risk, we looked at changes in population as changes in demand. Much as population demands dictated the current landscape in terms of land cover; future demands may also change the demand for certain ecosystem services. Population increases, in tandem with climate change, would mean an increase in demand and potential decrease in supply. Furthermore, different countries ‘use’ biodiversity in different ways. This is often measured by the ecological footprint defined as ‘the quantity of nature required to support people and their economies’. Thus, the greater the footprint is above one, the greater the amount of ecosystem services required to support the population. The footprints (EFs) for each of the countries in this study in 2015 are Brazil (2.9), China (3.7), Egypt (1.9), Ethiopia (1.1), Ghana (2.0), and India (1.2) (www.footprintnetwork.org). The equations used to develop the final natural capital risk index can be found in the SM.

The index is calculated by taking the remaining percentage of ecosystem services and reclassifying it using a non-linear reclassification. A non-linear scoring was chosen owing to an unknown amount of redundancy among the roles individual species play in an ecosystem, with the expectation that the risk will accelerate with increasing loss of species (Mace et al. 2012; Parmesan et al. 2022). The risk levels correspond to the following percent of ecosystem services remaining: 0.75–1 low; 0.55–0.75 low to medium; 0.4–0.55 medium; 0.3–0.4 medium to high; 0.2–0.3 high; 0.1–0.2 extreme; and <0.1 natural capital would have to be imported.

For each country, results are given for:

- (A) Natural capital risk from climate change alone.
- (B) Climate change plus 2010 population and 2015 landcover.
- (C) Climate change plus 2100 population, 2015 landcover.
- (D) Climate change plus 2100 population, 2015 landcover and 2015 ecological footprint.

The difference between C and D can be viewed as potential adaptation from behavioural changes (i.e., individuals reducing their ecological footprint to match the biocapacity of the country). Furthermore, the difference between A and B can be viewed as the adaptation potential from restoration of natural habitats or shifting to a sustainable land use. Of the countries in this study, only Brazil is in a biocapacity (amount of land necessary to support the population) ‘surplus’; the other countries exceed the natural capacity of their country to annually support the population. This difference is either met through importation of goods or by ‘borrowing’ from the future, using resources in a long-term unsustainable fashion. While it is true that the biocapacity of the land would also be changing (often reduced), reducing the ecological footprint would provide some adaptation potential at lower levels of warming, reducing as warming levels increased (and biocapacity decreased).

In this study, all urban areas are classified as needing to import natural capital. There are many reasons for this—for many ecosystem services, the value of the urban area is negative (the urban heat island negates cooling the air, impervious surfaces negate flood control) as well as spatial scale. A proper assessment of natural capital in urban areas would

require working with higher resolution data (e.g., 30 m or less as opposed to 300 m) to capture local green spaces and green rooftops. Thus, a proper urban natural capital risk assessment would likely need to be done on an urban area by urban area basis as opposed to a country or global scale.

Finally, some maps in the figures have unshaded areas (white) representing areas with incomplete data. Otherwise, dark blue represents water, light blue permanent snow and ice, dark purple are urban areas, and tan represents bare rock/sand.

3 Results

The baseline global state of the underlying ecosystems and potential ecosystem services can be found in Fig. 1. In the absence of people then all areas would be 'natural'. While there is a great deal of fragmentation of habitats globally, there are still areas that, at a spatial resolution of 300 m, have a land cover type that can be considered natural (greener) versus those predominantly agricultural (brown). One way of considering this is as a depleted bank for most ecosystem services but a key source for food production. Areas that are dark green and surrounded by brown (e.g., southwestern Ghana, Fig. 1e) have lost many areas to other uses (principally agriculture) that would otherwise have high natural capital.

Almost all ecosystem services considered here are reduced if biodiversity loss occurs. Thus, biodiversity can be considered as the overall available stock (or overall biocapacity) available for different human uses, which in Fig. 1 have been reduced by past land use change. The projected changes in overall global biodiversity due to climate change (Figure S2) imply further reductions in ecosystem services. The projected percent loss of biodiversity stocks due to climate change (as represented by declines in species richness) in natural versus agricultural lands in each country is presented in Figure S3. While the percentage declines in species richness differ between countries, within countries, the percentage declines in species richness are generally very similar at corresponding levels of global warming, suggesting that there are few differences in underlying potential biocapacity, based on climate alone, in natural versus agricultural lands. This suggests that one key adaptation to loss of ecosystem services is restoration of agricultural lands, or at least a substantial change to more sustainable farming practices (e.g., regenerative agriculture). Restoring agricultural lands (especially marginal agricultural lands) can improve the overall number of ecosystem services provided (including improving carbon uptake and storage) but with the loss of food provisioning. Similarly, regenerative agriculture will support a greater number of ecosystem services (including food provisioning) than industrial agriculture.

Figures S2 and S3 show the potential available stocks but does not take into full account how much potential ecosystem service area has been converted to food production. Figure S1 shows the percent of each country retaining 75% (50%) of its biodiversity (natural capital inventory) within land classified as natural, agricultural or urban in 2015 (ESA 2017). Bars labelled as agriculture represent potential adaptation space if restored to natural habitat, albeit at the loss of food production. The bars labelled green represent not only the natural capital within natural habitats but also the natural capital bank supporting agricultural and urban areas (e.g., by providing services that those landcover types are unable to support themselves). Urban areas that are modelled as potentially being able to support large percentages of biodiversity would benefit both people and biodiversity with a shift to a greener infrastructure. The overall potential adaptation opportunities decline

with increasing warming as projected potential losses of biodiversity increase. The greatest potential adaptation opportunity (via restoration) is available ($\leq 25\%$ projected loss in biodiversity climate space) at 1.5° versus 2° in Brazil (halving of potential) and India, falling to almost 0 by 3°C . In Egypt, the declines are even higher, and even 2° of warming potentially means no available adaptation opportunities for maintenance of 75% of the natural capital inventory. On the other hand, Ethiopia and Ghana fare well to 2°C with the greatest change coming between 2°C and 3°C . While far more land is available if a loss of species richness of 50% is considered acceptable (rather than a loss of 25%), this comes with the greater risk to ecosystem services (Parmesan et al. 2022).

3.1 Risk accrual within each country

In each of the Figs. 2, 3, 4, 5, 6 and 7 below, the top row of maps shows the natural capital risk owing to landcover (2015) and population alone (2010 population (top left), landcover plus 2100 population (top middle), and landcover plus 2100 population and 2015 ecological footprint (EF) (bottom right); subsequent rows are warming levels of 1.5, 2, 3 and 4°C with column a (leftmost maps) showing risk with climate change alone with no land cover or population changes, column b showing natural capital risk from combining climate change impacts on biodiversity with 2015 landcover and 2010 population (combining column a with the top left map, see SM), column c is equivalent to column b but uses the 2015 landcover and future population (2100), while column d adds EF as well.

3.1.1 Brazil

Current ‘baseline’ natural capital risk (Fig. 2, top left map) in many parts of Brazil is equivalent to that projected to occur from losses in biodiversity at warming levels of just over 2°C . However, in parts of Brazil, especially Amazonia, the risk from loss of natural capital at 1.5°C , owing to projected loss of climatic range of biodiversity, is greater than what has already occurred from other anthropogenic activities. Brazil is projected to undergo a reduction in natural capital inventory with $< 2^\circ\text{C}$ of warming (Figure S4) with a substantial reduction by 3°C . This is shown as an increase in risk to natural capital, based on projected losses of biodiversity climate space with increasing climate alone (Fig. 2a). Comparing column a with columns b–d suggests that while landcover change was formerly a major driver in natural capital risk (top maps), climate change is potentially a much larger future driver of increasing risk. This is a conservative view as the difference comes from immediate use of a resource by the inhabitants of the area (or country) versus impacts driven by expansion of economic activities (e.g., livestock production) for export, as has been a major driver of deforestation in Amazonia. Large declines in biodiversity are projected between 1.5°C and 2°C , and further declines between 2°C and 3°C , with 80–100% of natural land exposed to severe droughts more than 1 year in length at 3°C (Price et al. 2022, 2024). Even with 1.5°C warming, significant biodiversity loss is projected.

These changes drive reductions in natural capital (Fig. 2a–d), and the potential internally driven changes in natural capital owing to population growth, even with EF, show few changes beyond those having already occurred. This is scenario dependent, and different SSPs would have different population patterns and potential impacts on natural capital. While there are some climate impacts at 1.5°C (column a), it is the addition of the current landcover patterns that shift much of southcentral Brazil from medium–low

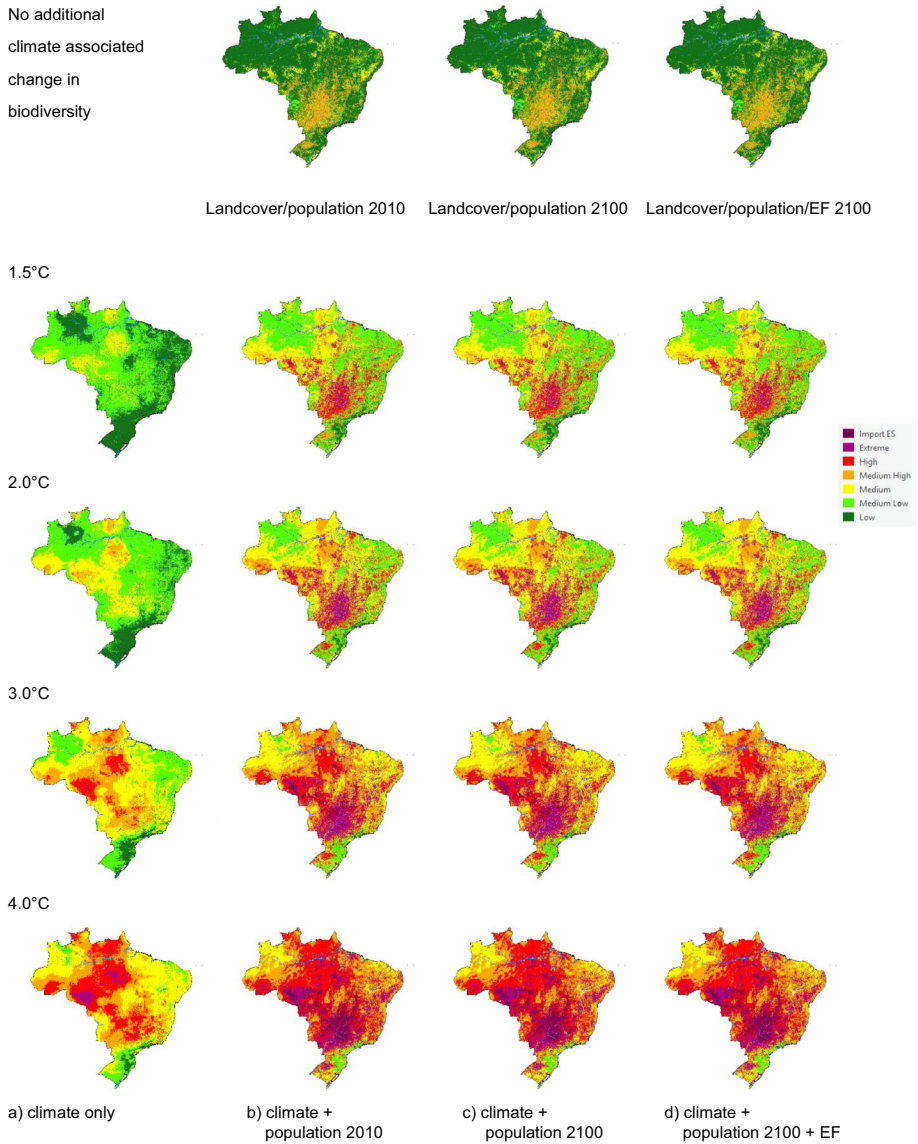


Fig. 2 Brazil natural capital risk at increasing levels of warming and changes in population. Brazil’s population of 165 million in 2000 is projected to increase by 11% in 2100 under SSP2

risk to high risk. Adding in additional climate change rapidly expands the area projected to be at high risk such that, by 3 °C, few areas are at low risk. The target temperature to minimize natural capital risk in Brazil is 1.5 °C (or lower).

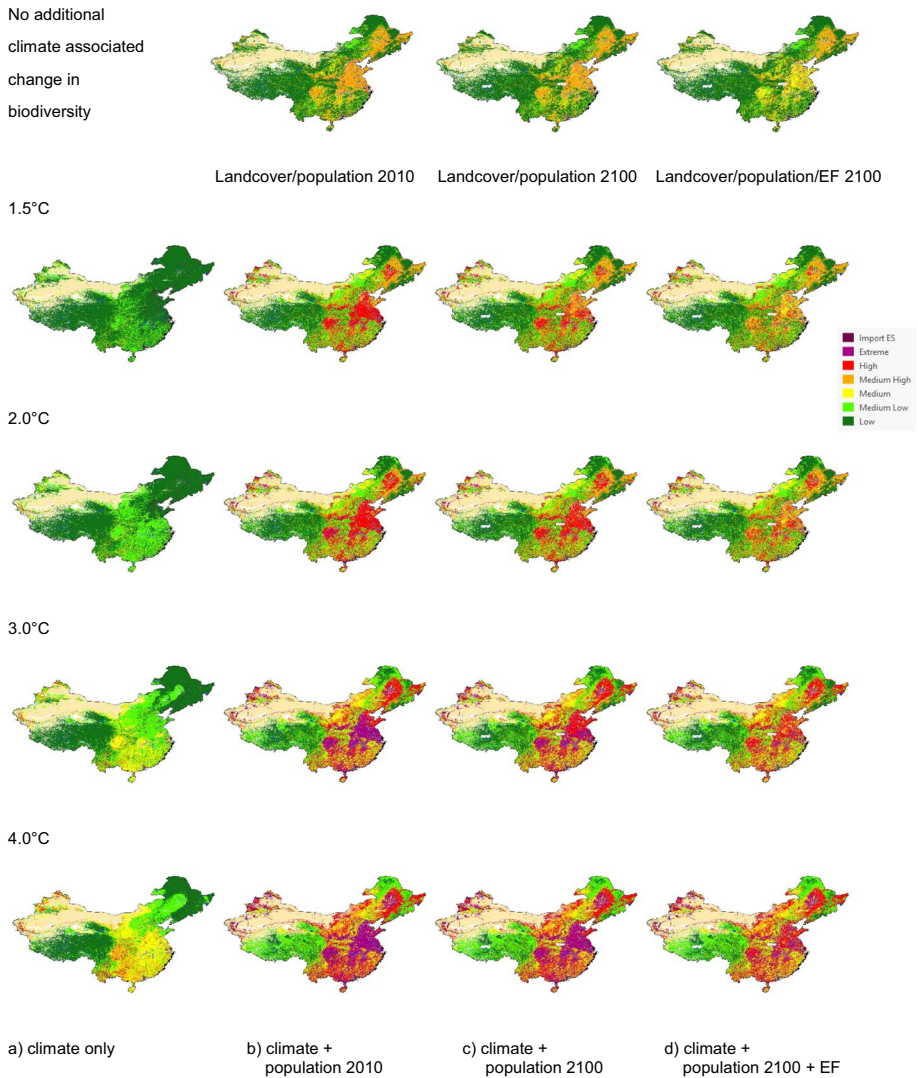


Fig. 3 China natural capital risk at increasing levels of warming and changes in population. China's population of 1.2 billion in 2000 is projected to decrease by 37% in 2100 under SSP2

3.1.2 China

Current 'baseline' natural capital risk (Fig. 3, top left map) in many parts of eastern China is greater than that seen to occur from projected losses in biodiversity, from climate alone, of greater than 4 °C. China is projected to undergo a substantial reduction in natural capital between 1.5 °C and 3 °C of warming (Figure S5). This can also be seen across biodiversity based on climate alone (Fig. 3a). The differences between column a and columns b–d show little additional impact from population change versus changes that have already occurred. Indeed, population shifts show a potential reduction in risk in parts of China, especially at

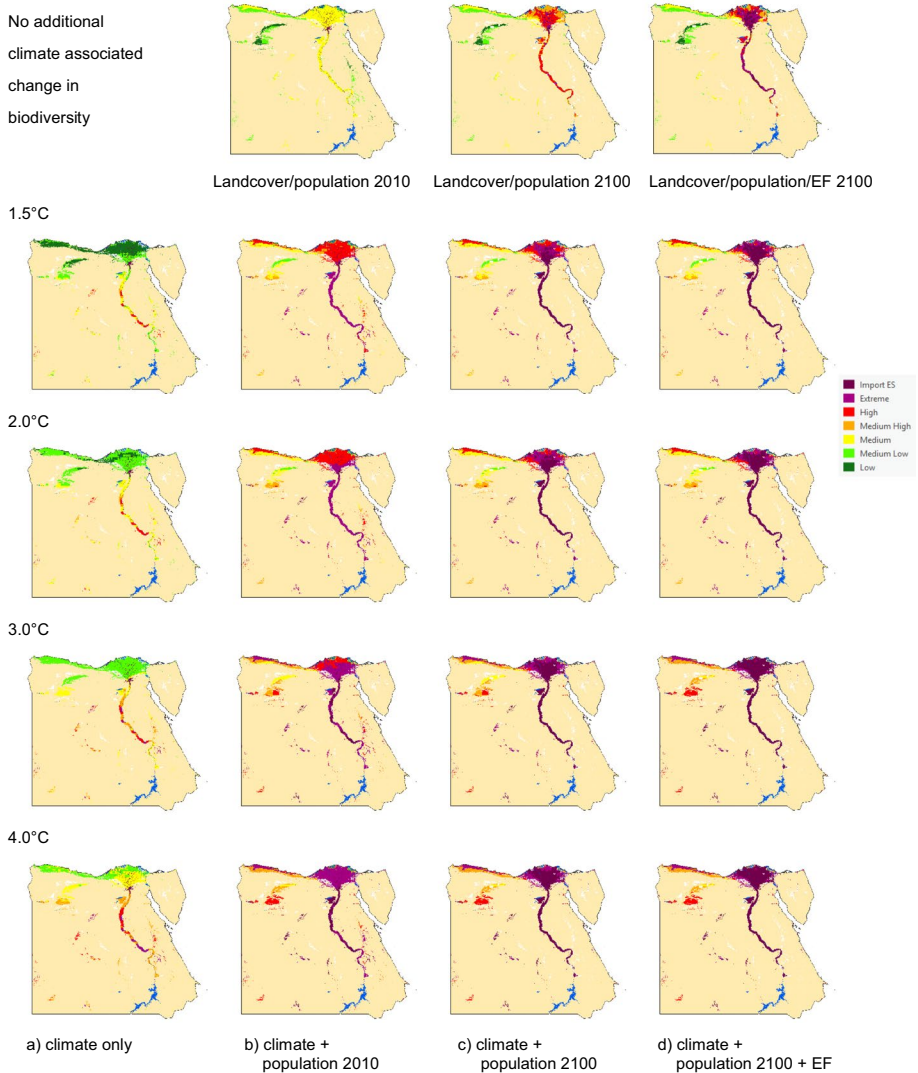


Fig. 4 Egypt natural capital risk at increasing levels of warming and changes in population. Egypt’s population of 67 million in 2000 is projected to increase by 94% in 2100 under SSP2

1.5 °C. Changes in climate lead to large declines in plant refugia for biodiversity between 1.5 °C and 2 °C, and further declines between 2 °C and 3 °C (Price et al. 2024). Limiting warming to 1.5 °C rather than 3 °C would potentially avoid 55% of the loss of plant refugia. Considerable benefits, in terms of reducing natural capital risk, would therefore accrue if global warming were limited to 1.5 °C. This would limit the amount of adaptation otherwise required, and potentially allow biodiversity more time to adapt naturally. As with Brazil, there are significant increases in risk owing to previous land conversion, especially in eastern China. These are areas where adaptation via restoration of natural habitats could be beneficial. China shows relatively minor increases in risk between 1.5 °C and 2 °C but

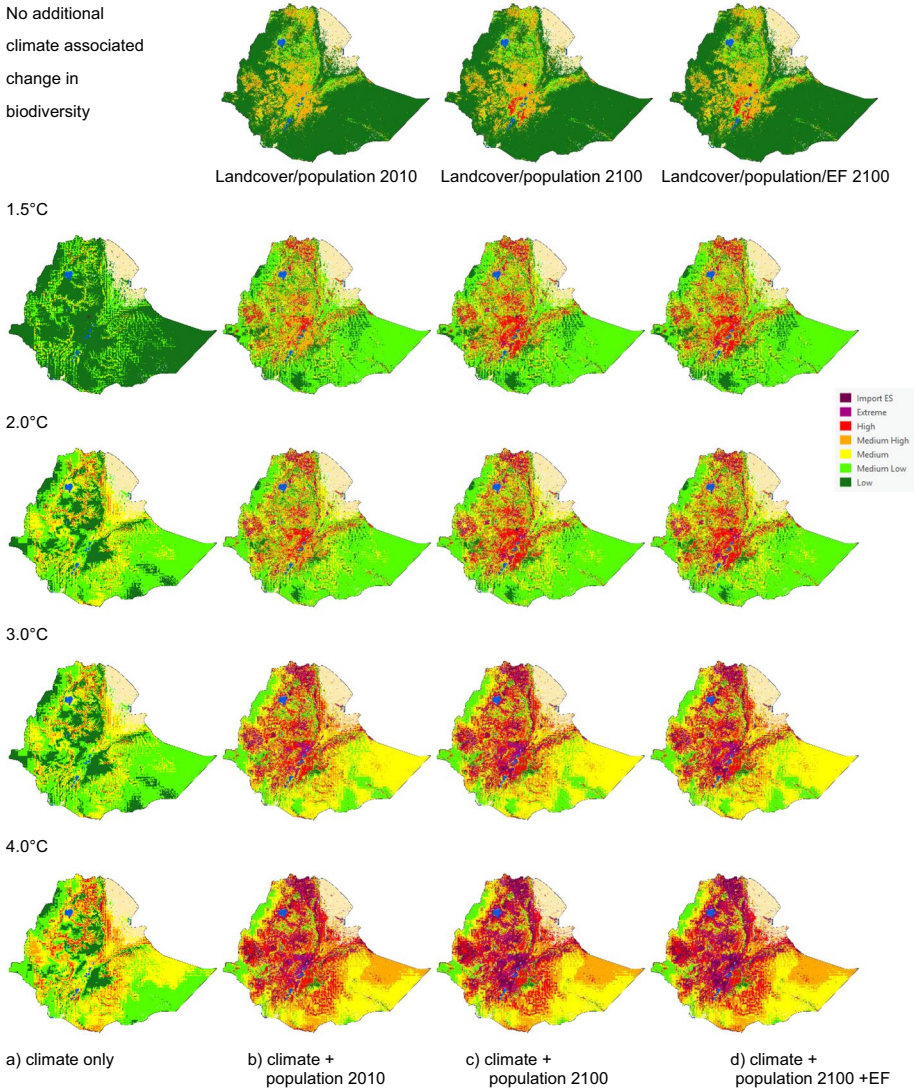


Fig. 5 Ethiopia natural capital risk at increasing levels of warming and changes in population. Ethiopia’s population of 63 million in 2000 is projected to increase by 203% in 2100 under SSP2

much larger increases above 2 °C. Therefore, the Paris Accords would still lower risk to natural capital in China.

3.1.3 Egypt

Portions of Egypt that are classified as bare rock/sand are excluded from this study. The biodiversity contained in these areas is often specialized and may not have been adequately sampled by the biodiversity models. However, Wadis and other vegetated

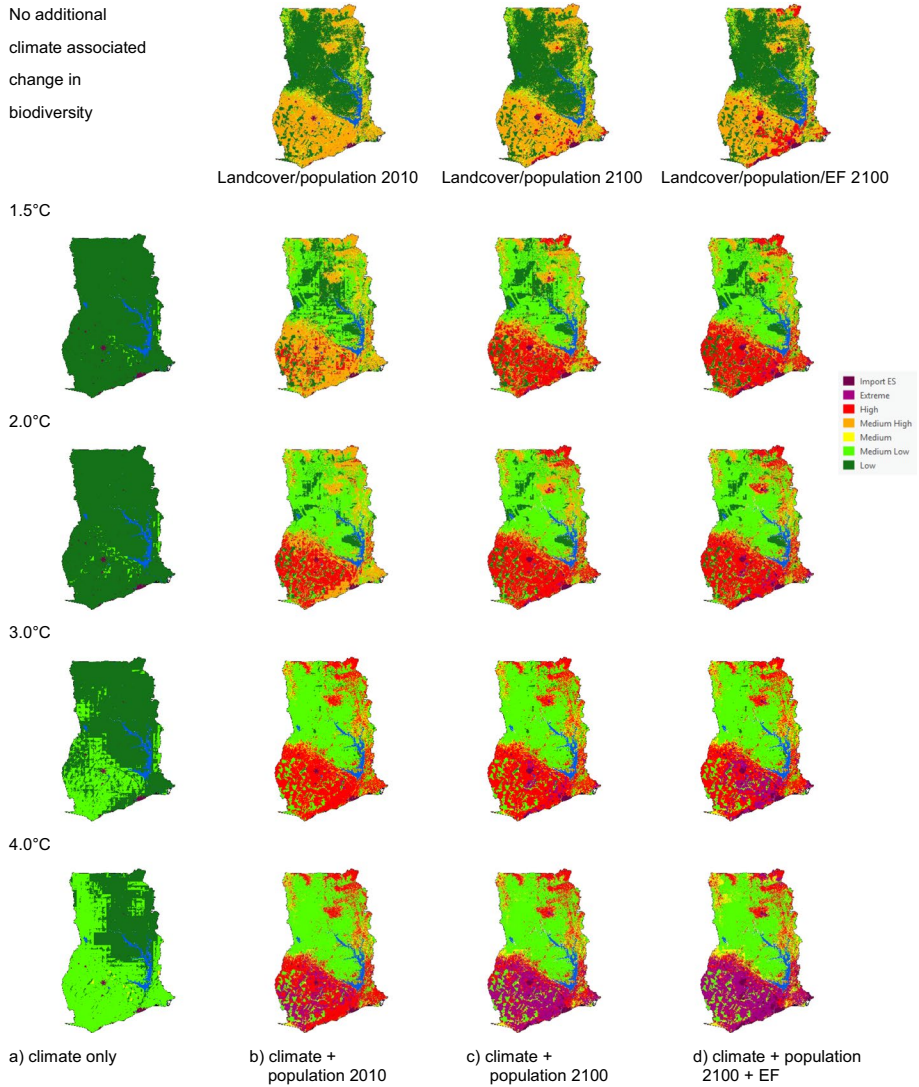


Fig. 6 Ghana natural capital risk at increasing levels of warming and changes in population. Ghana’s population of 19 million in 2000 is projected to increase by 195% in 2100 under SSP2

areas greater 90,000 m² (e.g., a single 300 m × 300 m pixel) are included but are difficult to see in the figures. Some ecosystems services (e.g., wood) are limited, and currently include exotic species. Overall, only 2% of the country is classified as natural land (as compared to bare ground), but even within this very small extent, the potential extent of climate refugia for plants is projected to decline with warming (Price et al. 2024). Current ‘baseline’ natural capital risk (Fig. 4, top left map) in many parts of Egypt is equivalent to that projected to occur from losses in biodiversity at warming levels of greater than 4 °C along the coast and 1.5 °C along the Nile. However, projected population growth

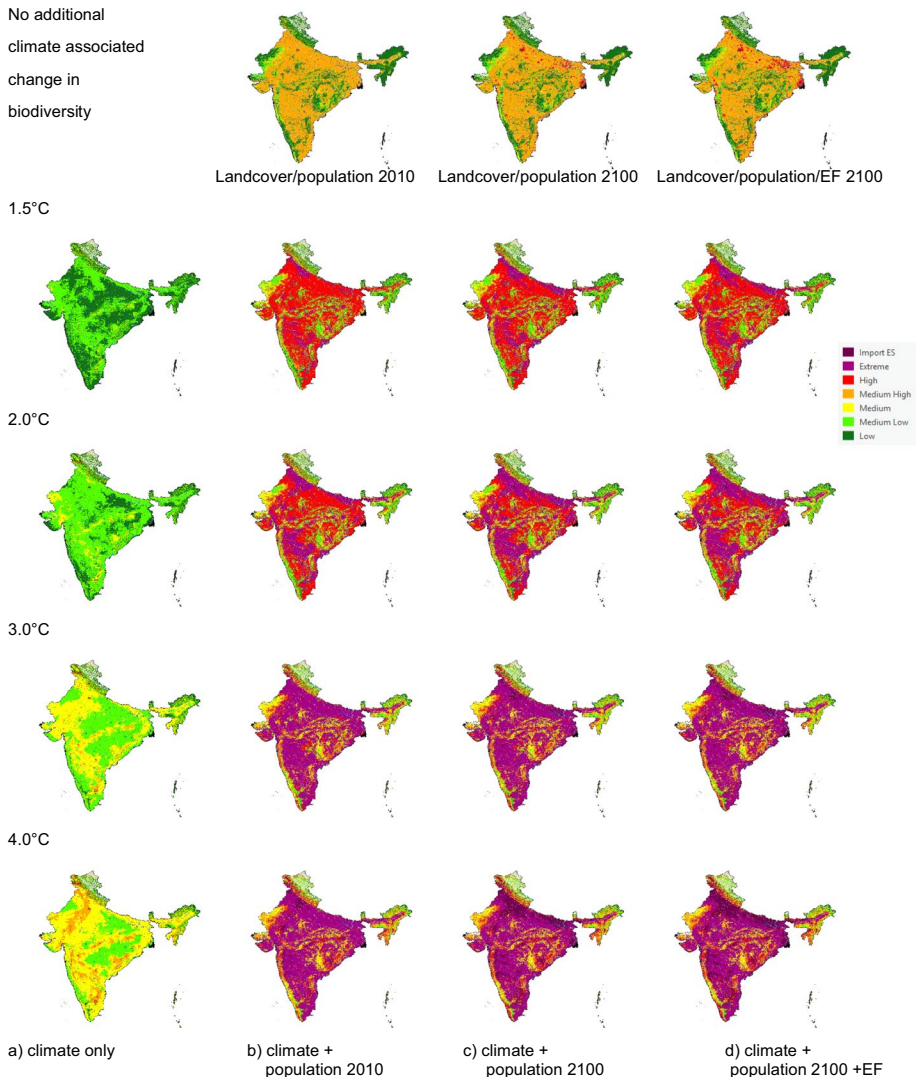


Fig. 7 India natural capital risk at increasing levels of warming and changes in population. India's population of 1.0 billion in 2000 is projected to increase by 62% in 2100 under SSP2

(SSP2) increases risk substantially more than that projected to occur from the impacts of climate change on biodiversity of warming of greater than 4 °C. Most natural capital is found along a narrow strip of land along the coast (Figure S6), and this area shows declines between 1.5 °C and 2 °C with substantial declines by 3 °C. The area along the Nile shows declines even at 1.5 °C (Fig. 4a). Factoring in current population levels, almost all of Egypt has natural capital at high to extreme risk at 1.5 °C (Fig. 4b). By 3 °C, much of the Nile is projected to be at high risk, with many areas needing to import natural capital. To avoid most of the natural capital risk in Egypt, warming would have to be held to below 1.5 °C.

3.1.4 Ethiopia

Seventy-five percent of Ethiopia is classified as natural, meaning it potentially provides a very important refuge for biodiversity as climate changes, especially $< 2^{\circ}\text{C}$ warming (Price et al. 2024). The potential projected impacts from climate alone show that much of Ethiopia would be able to maintain large amounts of its natural capital inventory at 2°C , except in the river valleys (Figure S7). By 3°C , lower elevations would already be seeing greater impacts. Population levels of 2010 and current land cover changes show the natural capital risk in many lower elevation areas to be moderate-high (Fig. 5b). Projected increases in population expand the area at high risk, even with 1.5°C warming (Fig. 5c, d). By 3°C , the combination of climate and population pressures potentially shifts much of the country into the high- to extreme-risk categories. Ethiopia could potentially see substantial reduction in natural capital risk if temperatures were held to 2°C or lower and could also see substantial benefits from land restoration.

3.1.5 Ghana

Limiting warming to $< 2^{\circ}\text{C}$ would potentially allow large amounts of most Ghanaian biodiversity to persist in remaining refugia. However, currently, some 50% of these areas are in agricultural use. Current 'baseline' natural capital risk (Fig. 6, top left map) in many parts of Ghana is greater than that seen to occur from projected losses in suitable climate for biodiversity of greater than 4°C . Areas converted to agriculture represent potential areas for restoration and recovery of natural capital. Figures S8 and 6a show the potential impacts from climate only, showing large areas maintaining 50% of their natural capital even at $3\text{--}4^{\circ}\text{C}$ warming. However, as with Ethiopia, adding in the natural capital demand via population substantially increases risk. While these areas may retain natural capital owing to climate change, population growth by 2100 pushes much of the southwestern part of the country from medium to high risk even at 1.5°C . By 3°C , population growth, coupled with the current EF, pushes parts of the country into extreme risk, especially in areas surrounding cities (Fig. 6d). By 2°C , only the existing protected areas in the south of the country maintain their natural capital, with the rest of the southwest part of the country at high risk. This indicates both the importance of protected areas but also the likelihood of an increasing amount of pressure on these areas from surrounding population growth. Natural capital in Ghana would be resilient even at higher levels of warming except from the pressure from population growth. However, a strong shift toward sustainable development could halt or reverse many of these negative projections.

3.1.6 India

Large declines of plant biodiversity in India are projected for 1.5 to 2°C of warming, and further between 2°C and 3°C warming. Many of areas that could act as plant refugia in India are already in agricultural use, but there are still important refugia remaining in the Western Ghats and the Himalayas (Price et al. 2024). Limiting warming to 1.5°C would avoid approximately 50% of the plant refugia loss otherwise projected to occur with 3°C warming. The potential impacts of climate change on biodiversity (as a whole, as opposed to just the plants above) can be seen in Figures S9 and 7a. These show that much of India would retain its natural capital (low risk) at 1.5°C with large increases in risk by 2°C .

With warming of 3 °C, very few areas are at low risk except for the Western Ghats and the Himalayas, and climate alone places most of the country at medium risk by 4 °C. Current ‘baseline’ natural capital risk (Fig. 7, top left map) in much of India is greater than that seen to occur from projected climate-induced losses in biodiversity of greater than 4 °C. Landcover change and population growth (Fig. 7b–d) shows most of the country at high risk, even at 1.5 °C. By 2 °C, few areas are at low risk. Thus, current human population pressures (column b) are equivalent to more than an additional 4 °C of warming. While risk begins to rapidly increase beyond 2 °C of warming, there is the potential for restoration providing adaptation and natural capital benefits at lower levels of warming.

4 Discussion

This paper reports on the initial results from the new framework and tool, WallaceNC. The modular design of WallaceNC allows for flexibility in its application in other parts of the world, with different or additional data, or by making other choices in its parameterization. The flexibility of the framework allows for switching to other climate change or biodiversity data (e.g., results from dynamic global vegetation models (DGVMs), or crop models), choosing different population growth scenarios, looking at different ecological footprints or looking at the role of global trade in increasing or decreasing demand on underlying land uses. WallaceNC provides the potential to use different landcover data, including regional landcover data at a higher resolution (e.g., 100 m² for the UK vs 90,000 m² used here). On the parameterization side, different choices could be made for the categorical weighting for most ecosystem services by landcover type. For example, the distance farmland is from natural habitat is known to play a role in the ability of wild pollinators to reach crops (Ricketts et al. 2008), and this distance could be used to more quantitatively weight pollination as an ecosystem service in farmlands. Alternatively, a crop filter including/excluding the need for insect pollination could be part of the weighting. Other uses could include investigating land-sharing/land-sparing possibilities (Phalan et al. 2011) or habitat restoration as part of mitigation activities.

Natural capital is frequently defined as the sum of the services that ecosystems directly or indirectly provide to humans. For example, the UK National Ecosystem Assessment defines “Ecosystem services are the benefits provided by ecosystems that contribute to making human life both possible and worth living.” Biodiversity is the living (or biotic) component of ecosystems meaning that it is one of the major components underpinning the ecosystem services. A given suite of species can have multiple ecosystem services, with individual organisms providing multiple independent services. Thus, declines in biodiversity, whether they have already occurred, or are projected to occur as the climate changes, can have a far greater impact on ecosystem services, and thus on natural capital. By examining the interrelationship between largely anthropogenic changes to landcover, population change, and projected impacts on species (and thus biodiversity and ecosystems), it is possible to estimate risk to natural capital with climate change, as well as some potential adaptation options.

IPCC assessments have examined the potential impacts of climate change on biodiversity, and local–global extinction risk. This is especially true of the most recent report, AR6 (Parmesan et al. 2022). If one considers changes in the climate space occupied by biodiversity alone, with no current landcover being considered, then the projected impacts of climate change on the six countries in this study can be seen in Figs. 2a, 3, 4, 5, 6, 7a, S2, and

S3. Of the six countries examined in this paper, with 1.5 °C warming, the projected biodiversity loss (in natural areas) ranges from 11.9% (China) to 33.3% (Egypt) with Ghana ranking close to China and Brazil close to Egypt. By 2.0 °C, the projected loss ranges from 15.3% (China, Ghana) to 37.8% (Egypt, Brazil), and by 3.0 °C, it ranges from 21.1% (Ghana) to 51.8% (Brazil).

While the projected impacts of climate change on biodiversity (as measured through loss of suitable climate space) are relatively high alone, factoring in the overall projected natural capital available with no climate change (the sum of the ecosystem services, Fig. 1a–f) shows that many areas in each country are already depleted in natural capital owing to changes in landcover over time. This is particularly true for Egypt, India, the southern third of Ghana (outside of protected areas), parts of Brazil, eastern China and the middle of Ethiopia. Translating this to natural capital risk, which factors projected changes in biodiversity, landcover changes in 2015 and population, even considering the potential for ecosystem redundancy (where some species replace or perform the services of species potentially becoming locally extinct), a much clearer picture of the potential risks (and subsequent potential damages) of climate change and use of natural resources arises.

In examining the natural capital risk from climate change alone (Figs. 2a, 3, 4, 5, 6 and 7a), even with 3 °C of warming, only some areas in Brazil, along the Nile in Egypt, and a few areas in Ethiopia and India are modelled as being at high natural capital risk. However, once ‘current’ landcover and population are added to the framework, large parts of Brazil, eastern China, Egypt, most of Ethiopia, the southwestern third of Ghana (except for protected areas) and almost all of India are modelled as being at high to extreme risk with 3 °C of warming. Even with 1.5 °C warming and current landcover and population, the combined risk to Brazil is similar to that seen between 2 °C and 3 °C from climate alone; whilst the combined risk in China, Egypt, Ghana and India is greater than the risk from 4 °C warming, and the combined risk in Ethiopia is greater than that of 3 °C warming alone. Thus, current land cover and population in these countries has led to substantial adaptation deficits (equating to the equivalent of 2 °C additional warming or greater), potentially leading to a soft adaptation limit (and, in some areas, potentially a hard adaptation limit). By 2100, factoring in population change (SSP2), current ecological footprint and current landcover, even with only 1.5 °C warming, large parts of Brazil, eastern China, most of Egypt, much of Ethiopia (approximately equal to the risk from climate alone at 4 °C), southwestern Ghana (except for protected areas) and most of India are at high to extreme risk with an adaptation deficit potentially equating to a soft adaptation limit.

Limiting warming to 1.5 °C rather than 3 °C substantially reduces natural capital risks, especially when considered in tandem with projected human population growth. Because risks remain even with 1.5 °C warming, an adaptation deficit is still present with soft adaptation limits in many countries. However, the amount of adaptation needed will be much less challenging for 1.5 °C warming than at higher levels. At lower levels, targeted restoration of agricultural habitats (even if restricted to marginal agricultural lands) would increase the natural capital bank available for use by people and providing support for remaining agricultural lands (fewer benefits could be achieved through regenerative agriculture, continuing to provide food but also supporting greater amounts of natural capital). For example, at 1.5 °C warming, converted lands that would have been projected to retain 75% of their biodiversity range from 44% in Ghana to 7.8% in Brazil (Figure S1). This is less an indication of a reduced land conversion in Brazil than it is a higher climate impact at lower temperatures. By 3 °C, the adaptation potential from restoration is substantially less: <1% in Brazil, India and Egypt; 7–8% in China and Ethiopia; but still 26% in Ghana. This indicates that adaptation option for biodiversity, and thus, natural capital, rapidly

decreases with increasing temperatures; what was an adaptation deficit has now become a hard adaptation limit.

These results look only at a single SSP, and other SSPs would produce different risk metrics. For example, SSP1 and SSP5 would potentially allow natural capital to start to recover as populations decline (depending on the spatial distribution of the population). However, SSP3 projects a substantially higher population, and this would likely lead to even greater losses of natural capital and higher risk. It is not just the size of the population, but also the consumption, measured here by the ecological footprint. None of the analyses in this paper includes the potential impacts of exporting natural resources on the overall natural capital, and this is a subject for future work. If developing countries become affluent and shift their diet and consumption patterns to match developed countries, the natural capital risk would also be expected to increase. Growth and economic development can take many different pathways to reach the same point, some with higher, and some with lower overall footprints. Similarly, this analysis only looked at current landcover, and not the large number of potential future landcovers that have been developed in integrated assessment models. However, many of these model outputs would have landcover that increases the adaptation deficit and natural capital risk. Protected areas, at least in some areas and up to some levels of warming, can provide important natural capital banks (e.g., as seen in Ghana, Fig. 6). However, in other areas, the biodiversity is so exposed to warming (Figure S2) that warming would need to be held to 1.5°, along with restoration and/or adaptation to reduce ecological footprints to hold natural capital risk to as low a level as possible. In these areas, meeting the Paris Accords is not enough to maintain natural capital; the adaptation deficit is too great (in this study, this includes large areas in India and Egypt), but all six countries have areas in adaptation deficit at 1.5 °C.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10584-023-03650-w>.

Acknowledgements We thank the members of BEIS Climate Science International who provided feedback to the study and the manuscript. We would also like to acknowledge Jeremy VanDerWal, Ian Atkinson and the eResearch Centre at James Cook University for their work with us in developing the original Wallace Initiative database.

Funding The study was funded by the UK Department for Business, Energy & Industrial Strategy (BEIS).

Data availability Data available on request.

Declarations

Competing interest No competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Balvanera P et al (2017) Ecosystem services. In: Walters M, Scholes R (eds) *The GEO handbook on biodiversity observation networks*. Springer, Cham. https://doi.org/10.1007/978-3-319-27288-7_3
- Boone RB, Conant RT, Sircely J, Thornton PK, Herrero M (2018) Climate change impacts on selected global rangeland ecosystem services. *Glob Change Biol* 24(3):1382–1393
- Brenkert AL, Malone EL (2005) Modeling vulnerability and resilience to climate change: a case study of India and Indian States. *Clim Change* 72:57–102
- Elias MA, Borges FJ, Bergamini LL, Franceschinelli EV, Sujii ER (2017) Climate change threatens pollination services in tomato crops in Brazil. *Agr Ecosyst Environ* 239:257–264
- ESA (2017) Land cover CCI product user guide version 2. Tech Rep. http://maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf
- Ferreira P, van Soesbergen A, Mulligan M, Freitas M, Vale MM (2019) Can forests buffer negative impacts of land-use and climate changes on water ecosystem services? The case of a Brazilian megalopolis. *Sci Total Environ* 685:248–258
- Fu Q, Li B, Hou Y, Bi X, Zhang X (2017) Effects of land use and climate change on ecosystem services in Central Asia's arid regions: a case study in Altay Prefecture, China. *Sci Total Environ* 607:633–646
- Gao J (2017) Downscaling global spatial population projections from 1/8-degree to 1-km grid cells. NCAR Technical Note NCAR/TN-537+STR. <https://doi.org/10.5065/D60Z721H>
- Giannini TC, Acosta AL, Garófalo CA, Saraiva AM, Alves-dos-Santos I, Imperatriz-Fonseca VL (2012) Pollination services at risk: bee habitats will decrease owing to climate change in Brazil. *Ecol Model* 244:127–131
- Giannini TC, Acosta AL, da Silva CI, de Oliveira PEAM, Imperatriz-Fonseca VL, Saraiva AM (2013) Identifying the areas to preserve passion fruit pollination service in Brazilian Tropical Savannas under climate change. *Agr Ecosyst Environ* 171:39–46
- Giannini TC, Costa WF, Cordeiro GD, Imperatriz-Fonseca VL, Saraiva AM, Biesmeijer J, Garibaldi LA (2017) Projected climate change threatens pollinators and crop production in Brazil. *PLoS One* 12(8):e0182274
- IPBES (2019) Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Díaz, S, Settele, J. et al (eds). IPBES secretariat, Bonn, Germany. p 56
- Jiang C, Li D, Wang D, Zhang L (2016) Quantification and assessment of changes in ecosystem service in the Three-River Headwaters Region, China as a result of climate variability and land cover change. *Ecol Ind* 66:199–211
- Jones B, O'Neill BC (2016) Spatially explicit global population scenarios consistent with the Shared Socio-economic Pathways. *Environ Res Lett* 11:84003. <https://doi.org/10.1088/1748-9326/11/8/084003>
- Leh MD, Matlock MD, Cummings EC, Nalley LL (2013) Quantifying and mapping multiple ecosystem services change in West Africa. *Agr Ecosyst Environ* 165:6–18
- Liu W, Zhan J, Zhao F, Yan H, Zhang F, Wei X (2019) Impacts of urbanization-induced land-use changes on ecosystem services: a case study of the Pearl River Delta Metropolitan Region, China. *Ecol Ind* 98:228–238
- Lovett A, Turner K, Stünnenberg G, Ferrini S, Stephanou E, and Greaves S (2018) A Natural Capital Asset Check and Risk Register for the Anglian Water Combined Services Area. Report to Anglian Water Services Ltd March 2018. <https://www.anglianwater.co.uk/siteassets/household/in-the-community/natural-capital-asset-check-report-2018.pdf>
- MA (Millennium Ecosystem Assessment) (2005) *Ecosystems and human well-being: synthesis*. Washington, DC: Island Press. <http://www.millenniumassessment.org/documents/document.356.aspx.pdf>
- Mace GM, Norris K, Fitter AH (2012) Biodiversity and ecosystem services: a multilayered relationship. *Trends Ecol Evol* 27:19–26
- McDonald RI, Mansur AV, Ascensão F et al (2020) Research gaps in knowledge of the impact of urban growth on biodiversity. *Nat Sustain* 3:16–24. <https://doi.org/10.1038/s41893-019-0436-6>
- O'Neill BC, Kriegler E, Ebi KL, Kemp-Benedict E, Riahi K, Rothman DS, van Ruijven BJ, van Vuuren DP, Birkmann J, Kok K, Levy M, Soleckim W (2017) The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob Environ Chang* 42(2017):169–180
- Parmesan C, Morecroft MD, Trisurat Y et al (2022) Terrestrial and Freshwater Ecosystems and their Services. In: Pörtner H-O, Roberts DC, Tignor M, et al (eds) *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA. Pp 197–377. <https://doi.org/10.1017/9781009325844.004>

- Pettinotti L, de Ayala A, Ojea E (2018) Benefits from water related ecosystem services in Africa and climate change. *Ecol Econ* 149:294–305
- Phalan B, Onial M, Balmford A, Green RE (2011) Reconciling food production and biodiversity conservation: land sharing and land sparing compared. *Science* 333(6047):1289–1291. <https://doi.org/10.1126/science.1208742>
- Price J, Warren R, Forstnerhaeusler N, Wallace C, Jenkins R, Osborn TJ, VanVuuren DP (2022) Quantification of meteorological drought risks between 1.5°C and 4°C of global warming in six countries. *Climatic Change* 174:12. <https://doi.org/10.1007/s10584-022-03359-2>
- Price J, Warren R, Forstnerhaeusler N (2024) Quantification of biodiversity risks between 1.5°C and 4°C of global warming in six countries. *Climatic Change* (in press)
- Ricketts T, Regetz J, Steffan-Dewenter I et al (2008) Landscape effects on crop pollination services: are there general patterns? *Ecol Lett* 11:499–515. <https://doi.org/10.1111/j.1461-0248.2008.01157.x>
- Rogelj J, den Elzen M, Höhne N, Fransen T, Fekete H, Schaeffer R, Sha F, Riahi K, Meinhausen M (2016) Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nat Clim Chang* 534:631–639
- Saunders SP, Grand J, Bateman BL, Meek M, Wilsey CB, Forstnerhaeusler N, Graham E, Warren R, Price J (2023) Integrating climate change refugia in 30 by 30 conservation planning in North America. *Front Ecol Environ* 21(2):77–84. <https://doi.org/10.1002/fee.2592>
- Song W, Deng X (2017) Land-use/land-cover change and ecosystem service provision in China. *Sci Total Environ* 576:705–719
- Talukdar S, Singha P, Mahato S, Praveen B, Rahman A (2020) Dynamics of ecosystem services (ESS) in response to land use land cover (LU/LC) changes in the lower Gangetic plain of India. *Ecol Ind* 112:106121
- Tang Z, Sun G, Zhang N, He J, Wu N (2018) Impacts of land-use and climate change on ecosystem service in Eastern Tibetan Plateau, China. *Sustainability* 10(2):467
- Tolessa T, Senbeta F, Kidane M (2017) The impact of land use/land cover change on ecosystem services in the central highlands of Ethiopia. *Ecosyst Serv* 23:47–54
- Wang H, Zhou S, Li X, Liu H, Chi D, Xu K (2016) The influence of climate change and human activities on ecosystem service value. *Ecol Eng* 87:224–239
- Warren R, Price J, Graham E, Forstnerhaeusler N, VanDerWal J (2018) The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5° C rather than 2° C. *Science* 360(6390):791–795
- Woldegerima T, Yeshitela K, Lindley S (2017) Ecosystem services assessment of the urban forests of Addis Ababa. *Ethiopia Urban Ecosystems* 20(3):683–699

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.