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Nature-based solutions promote climate change adaptation safeguarding ecosystem services

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1. Introduction

Climate change is upon us. It is virtually certain that humans will face the consequences of climate change in the near future (IPCC 2014; IPCC, 2018). Current trajectories predict high climate change until the end of the century, with global mean temperature increases beyond 4 °C (IPCC 2014). In addition to direct impacts on human systems, climate change may lead to drastic abrupt changes on social-ecological systems, jeopardising nature's essential contributions to people (i.e. ecosystem services; Breshears et al. 2011, IPBES 2019, Thonicke et al. 2020, Chaplin-Kramer et al. 2019). Efforts to de-escalate climate change, such as those in the Paris Agreement, aim to limit the increase in temperature to below 2 °C by the end of the century through extensive climate mitigation (UNFCCC 2015). Thus, mitigation is imperative to keep impacts as low as possible, likely leading to substantial reductions of negative impacts on ecosystems and the services they provide (IPCC 2018, IPBES 2019, Manes et al. 2021, Lenton et al. 2019, Warren et al. 2018). However, climate change is not preventable anymore. Even with successful mitigation strategies, we will not be exempt from the negative impacts of climate change (e.g. Nunez et al. 2019), although to a lessened extent. Thus, we can no longer rely solely on mitigation, having already entered the climate change adaptation era (IPCC, 2014; IPCC, 2019; Scarano et al. 2020).

Climate change adaptation is based on actions that reduce impacts and increase system's resilience (IPCC 2014). In particular, for human systems, adaptation refers to reducing, moderating and/or avoiding potential or future risks (IPCC, 2014; IPCC, 2018). For societies to cope with high climate change and in face of an uncertain future, adaptation needs to be ongoing, holistic and transformative (Smith et al. 2011, Colloff et al. 2017). It is crucial to anticipate impacts and ponder the repercussions of different decision-centred development pathways, to choose the best action to adapt to new climatic conditions (i.e. a road map to effective adaptation) (Wise et al. 2014, Thonicke et al. 2020). Such development pathways are composed of interventions that are essentially rooted in land-use change and policy (hereafter 'land-use interventions', Rezende et al. 2018). These land-use changes and policies have a great influence on the provision of ecosystem services (Fedele et al. 2018, Van Oudenhoven et al. 2012, IPCC 2019). Many land-use interventions are particularly valuable due to the potential of faster implementation compared to the longer-term effects of climate (Newbold 2018). Ongoing land-use interventions implemented in the present have the potential to promote adaptation by attenuating or even preventing climate change impacts in the future (Pires et al. 2017). However, the adaptive potential of such development pathways in face of climate change (i.e. how effective they are in increasing climate change adaptation) is still little known.

Different development pathways can profoundly impact ecosystems and increase or decrease the flow of their benefits to people (IPBES 2019). Human-centred development pathways focus on economic growth through interventions that include urban and agricultural expansion or that directly extract goods from nature (e.g., Eigenbrod et al. 2011). It is expected that such a pathway prioritises benefits in the form of provisioning services, aiming for direct goods such as enhancing the production of food and extraction of raw materials (McElwee et al. 2020). Conversely, development pathways that aim to lessen human footprint on the planet can act as a 'middle-of-the-road' between economic growth and nature conservation. Such a pathway advocates for a decelerating world, for example, through urban shrinkage, which has

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already been linked to benefits for ecosystem services (e.g., Lauf et al. 2014). Lastly, nature-centred development pathways are based on the concept of nature-based solutions, including interventions such as ecosystem-based adaptation (Cohen-Shacham et al. 2016, Scarano 2017). Nature-based solutions promote benefits, especially for services that are closely linked and intrinsically related to ecosystem integrity, such as supporting or regulating services (Benayas et al. 2009). The recognition that best-choice action must be taken to ensure a safe climatic future and the flow of benefits between nature and people is especially critical given the many environmental agreements being set on upcoming international conventions. However, there is no synthesis in the scientific literature on the adaptive potential, or quantification of impact reduction associated to different development pathways to inform policy-makers.

Here, we evaluate the adaptive potential of three different development pathways — "Human Development", "Reduced Footprint" and "Nature-based Solutions" — to reduce climate change risks over ecosystem services. Through a meta-analytical approach, we provide a synthesis of the available literature and explore various aspects of this issue: (i) the effect of mitigating climate or leaving climate change unchecked for ecosystem services provisioning, (ii) the potential of each pathway to counteract climate change both under a low (mitigated) and a high climatic change state, and (iii) the geographic bias on knowledge in this topic and trends related to each development pathway across the globe. We discuss the advantages and the context-dependence of each pathway for ecosystem persistence under climate change and how the choice of the pathway may create trade-offs or opportunities among multiple ecosystem services.

2. Methods

2.1. Literature search

We searched in the *Web of Science* database on November 2018 for papers that used in their titles, abstracts and keywords the terms: ("climate change" or "land-use change" or "land use change") and ("ecosystem service*" or "nature's contribution to people" or "NCP" or "environmental services") and future decades until the end of the century (2030 to 2100). We used these terms to assemble papers that predicted the impact of climate change into the future and the potential of several land-use interventions to establish alternative development pathways until the end of the century. Thus, papers that did not provide numerical results of current and future predictions (e.g. review papers) were excluded. We used both "ecosystem services" and "nature's contribution to people" (here used as synonyms) because of the growing literature that depicts both terms when investigating human relation with nature (see Díaz et al. 2018, Peterson et al. 2018, and Pires et al. 2020). The search yielded 294 papers, from which we used 138 that evaluated the impacts of land-use interventions and climate change on ecosystem services. We established different development pathways based on land-use interventions, categorized ecosystem services into groups, compared the effectiveness of pathways to reduce climate change risks and evaluated the magnitude of difference between current and future times in each case, as detailed below. See Supplementary Table 1 for all data extracted from each study.

2.2. Establishing development pathways

We compared the impacts of climate and land-use change interventions on ecosystem services by establishing development pathways. Land-use change was pivotal to define the three alternative pathways: i) the *Human Development pathway* evaluates continuous or increased business-as-usual trends towards economic growth, including urban or agricultural expansion, development-focused policy and nature exploitation; ii) the *Reduced Footprint pathway represents a 'middle-of-the-road' pathway,* evaluating lessened business-as-usual trends, such as urban shrinkage; and iii) the *Nature-based Solutions pathway* evaluates actions centered on nature conservation, land recovery and protection, such as reforestation or protected area expansion. The three development pathways were defined based on the well-established literature trend of human-centered versus nature-centered interventions, plus a middle-of-the-road pathway which was defined as Reduced Footprint according to the scenarios used in the papers assessed in the review. The interventions depicted in each of the assessed papers were classified according to which pathway they were consonant with, regardless of explicitly using this terminology or not. These development pathways were assessed independently to determine their impact on ecosystem services in the absence of climate change, and in combination with two contrasting climate change conditions based on IPCC (2018) and Paris Agreement threshold of below and above 2 °C warming level: i) *High climate change,* where climate change is not addressed, leading to warming levels of above 2 °C in relation to pre-industrial levels, according to IPCC (2018) thresholds; and ii) *Low climate change,* where climate mitigation is implemented reaching warming levels of below 2 °C in relation to pre-industrial times (see Supplementary Table 2 for further information on the classification criteria for the pathways).

We compared the impacts of climate change on ecosystem service provisioning, either high or low, to the effects of pursuing each of these three development pathways together with a changing climate. The difference between the impacts of climate change alone to the impacts of climate change in concomitance with each development pathway allowed evaluating their adaptive potential (i.e. if and how much they were able to reduce climate change impacts) and trade-offs on different ecosystem services.

We identified four drivers of change for each development pathway: i) *Policy/management*, where studies were based on holistic political or economic decision-making or direct management. Policy/management is a driver according to each development pathways' assumptions. Thus, under Human Development and Reduced Footprint, the policy/management decision-making enhances or lessens development demand, respectively, whereas for Nature-based Solutions decision making leans towards sustainability; ii) *Nature intervention*, where studies are based on any intervention that degrades/exploits (Human Development), reduces degradation (Reduced Footprint) or preserves nature (Nature-based Solutions); iii) *Agriculturalization*, where studies enhance (Human Development) or lessen agricultural intensity (Reduced Footprint) and; iv) *Urbanisation*, where studies depict urban expansion (Human Development) or shrinkage (Reduced Footprint). No studies assessed the effect of Agriculturalization or Urbanisation drivers over Nature-based Solutions pathways. The absence of drivers in these studies was not determined a priori, but resulted from the approaches used in the papers retrieved.

We also compared the potential impact of the three development pathways on all ecosystem services in the absence of climate change to understand their isolated effect. To do so, we compared studies that only considered land-use change interventions ignoring climate change in their analysis, and classified them into each of the three development pathways. This way we had, in each development pathway, studies with and without climate change. We also explored potential geographic biases in the current scientific knowledge and trends at the global scale by comparing the proportion of countries assessed in the studies (e.g. if the majority of studies assessed countries in the global north or south). The identification of regionalised opportunities and caveats can back policy arrangements in international environmental agreements.

2.3. Ecosystem services classification

According to the available data and inspired on TEEB Foundations (2010), we further allocated our data into nine ecosystem services and categorized them into provisioning, regulating, cultural or supporting services groups (MEA 2005). Provisioning services included food/crop provision, raw materials provision and water provision. Regulating services included carbon sequestration, coastal protection, water and flood regulation, and soil erosion and nutrients control. Due to lack of data, cultural services were merged into one group including aesthetic value, recreation and tourism. Supporting services were represented by biodiversity and supporting habitat-related services (see Supplementary Table 2 for further information on the classification criteria of ecosystem services).

2.4. Data analysis

We obtained measures of the current state of all ecosystem services assessed and potential future impacts considering the alternative pathways from all papers. When papers provided projections for several years into the future, we preferably selected the potential implications for 2050 and 2100, which were the most assessed future years among the retrieved papers. When the paper did not provide projections for 2050 and 2100, we selected the prediction for the latest year provided closest to those years.

We established the difference between current and future time frames using percentual differences of indicators as the metric of effect size. Positive values represent increases in ecosystem services provisioning while negative values represent a decrease. To avoid bias in comparing estimates for different timespans, we standardised the impact measures by their timespan (i.e., our effect size was calculated using percentage differences between current and future times, divided by the number of years in the timespan). As a consequence, our mean effect size can be understood as a rate and cumulative through time. However, it is important to highlight that although the effect size was calculated as a rate, we do not imply that impacts follow linear yearly increments. This standardisation also allowed direct comparisons from all impacts regardless of the study period. If the paper provided values for more than one local site (i.e., carbon stock in several forest transects or soil carbon in several depths underground, impacts over different rivers or cities), we calculated the effect size considering the mean value. Similarly, we also computed means for effect sizes of more than one focal species (i.e., habitat loss for multiple species). If the paper only displayed results in graphical formats, we extracted values using the software Data Thief III version 1.7 (Tummers 2006).

The collection of all potential impacts from all studies on ecosystem services resulted in 787 measures of effect size. We compared the effect of the alternative development pathways on ecosystem services by running a set of analysis on the effect sizes. To understand the adaptive potential (i.e. climate adaptation effectiveness) of each pathway under low and high climate change, we produced a heat map comparing the potential impacts of each pathway for all ecosystem services. The heat map was made using effect size values for each development pathway and ecosystem service. We built a set of generalised linear mixed models (GLMMs) considering the alternative pathways as a fixed factor and the study's identity as a random factor for each ecosystem service. The study's identity as a random factor reduces potential bias and potential correlations stemming from multiple measures being obtained from the same study. We also investigated each development pathways' trade-offs and overall behaviour in the absence of climate change using polar plots (Supplementary Material).

To understand the factors driving changes in each pathway, we evaluated the proportion of effect sizes stemming from each driver of change and the variance of effect sizes within confidence intervals for each pathway in each ecosystem service. This approach also allowed investigating the biases related to the influence of each driver (policy/management, nature intervention, agriculturalization and urbanisation) on the overall pattern of each development pathway. To understand the global effects of each pathway, we compared the effect of the pathways considering the mean effect size values considering all ecosystem services. To assess the significance of increases or decreases within these global effects for each pathway under high and low climate change, we performed one-sample t-tests, considering the effect size values against a hypothetical mean value equals zero. We investigated geographic bias in the literature using plotted maps of each country's quantity of effect size values.

We ran statistical analysis using the *nlme* package (Pinheiro et al. 2020) and polar plots figures using the *ggplot2* package (Wickham 2016) in the R software (R Core Team 2019). All other graphs were created using GraphPad Prism software version 8.0.1 (GraphPad Software, www.graphpad.com). We created maps using ArcMap 10.5.

3. Results

Our synthesis of the literature reveals that climate change negatively impacts ecosystem services, although all development pathways were able to reduce the impact's magnitude (Figs. 1-3). On a global scale and considering all types of services, the mean effect of climate change showed prominent negative impacts, both under high and low climatic changes (one-sample t-test, $P < 0.05$, Fig. 1). However, the mean effect of the three development pathways reveal their adaptive potential. Reduced Footprint and Human Development pathways effectively reduced climate change risks, especially in low climate change (one-sample t-test, $P > 0.05$, Fig. 1). However, Nature-based Solutions was the only pathway that could globally counteract climate change while producing positive impacts across ecosystem services, and benefits reached higher magnitudes under mitigated climate change (GLMM, $P = 0.05$, Supplementary Table 3, Fig. 1).

Otherwise, we reveal that studies over the impacts of climate change on ecosystem services and the adaptive potential of development pathways are concentrated in a few countries (Supplementary Fig. 1). We show geographic bias on ecosystem services assessments worldwide with studies majoritarily concentrated in the United States, China and Europe (Supplementary Fig. 1). More than 25% of our data is based solely on assessments on the United States (Supplementary Fig. 1, Supplementary Table 1). Precisely, although the majority of studies worldwide investigated the effects of Human Development pathways, Nature-based Solutions' potential was only investigated in 10 different

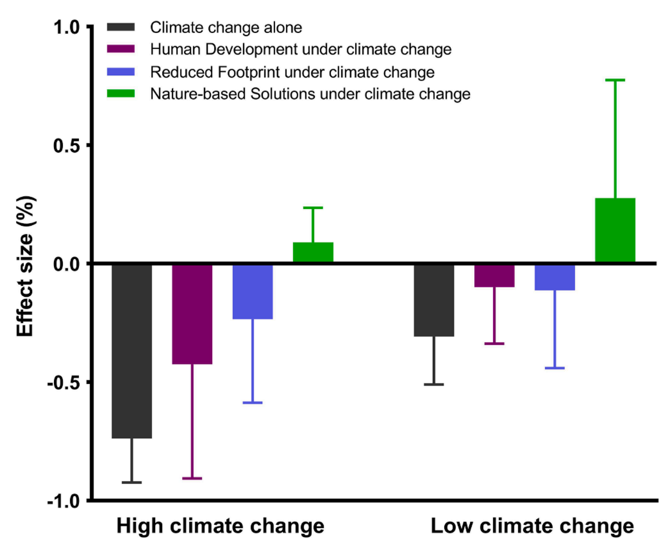


Fig. 1. Mean impacts of climate change across all ecosystem services globally and the adaptive potential of development pathways. The figure shows the mean effects of climate change alone and together with each alternative pathway on all ecosystem services. Bars represent increases (positive) and decreases (negative) in ecosystem services with confidence intervals. High climate change corresponds to a state where climate change is not addressed and low climate change corresponds to a state where climate mitigation is implemented, leading to warming levels of above and below 2 °C in relation to pre-industrial levels, respectively (IPCC 2018). Statistical comparisons between climate change alone and the pathways within high and low climate change contexts for all ecosystem services are described in Supplementary Table 3.

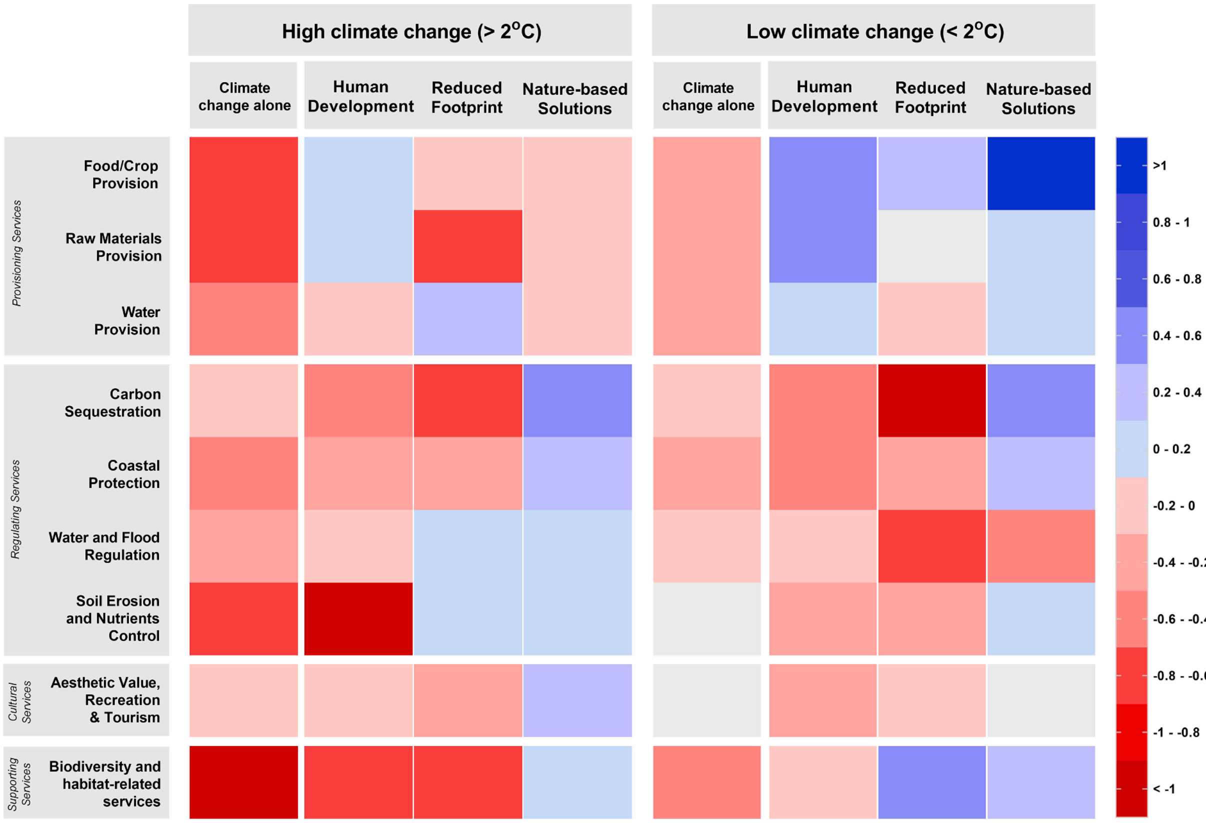


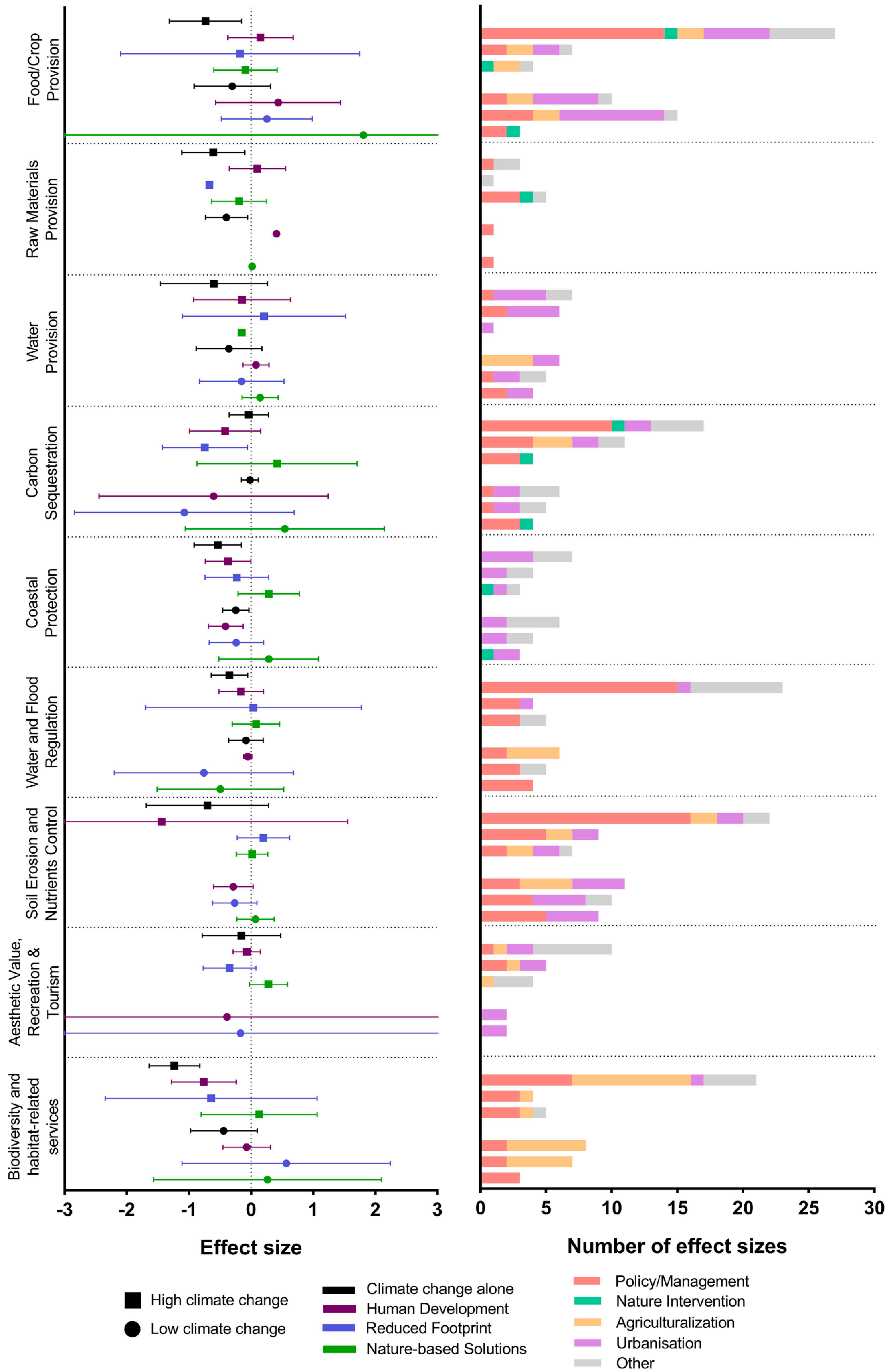
Fig. 2. The impact of development pathways under different climatic contexts for each ecosystem service. The figure shows the potential of three different development pathways to revert the negative impacts stemming from climate change (high and low) on nine groups of ecosystem services (for a detailed description of the pathways refer to Methods and Supplementary Table 2). Mean effects of climate change alone are compared to effects of climate change with each alternative pathway. High climate change corresponds to a state where climate change is not addressed and low climate change corresponds to a state where climate mitigation is implemented, leading to warming levels of above and below 2 °C in relation to pre-industrial levels, respectively (IPCC 2018). Decreases (red gradient) and increases (blue gradient) range from < -1 to > 1, respectively. Statistical comparisons between climate change alone and the pathways within climatic contexts inside each ecosystem service are described in Supplementary Table 5.

countries in the Northern hemisphere, especially in the United States and Europe (Supplementary Table 1).

The magnitude of the effects of different pathways was dependent on climate change intensity and the type of ecosystem services. High climate change overall led to substantially greater negative impacts than low climate change across all ecosystem services (Figs. 1-3). Climate mitigation reduced risks, on average, by half for all ecosystem services, ranging from between 36% and 77% of risk reduction (Fig. 2, Supplementary Table 4). Mitigation was especially effective to reduce risks from high climate change for food/crop provision, raw materials provision and biodiversity and habitat-related services (Fig. 2, Supplementary Table 4). Low climate change still led to adverse effects on all ecosystem services, but the three development pathways were able to reduce risks for almost all of them (Fig. 2, Fig. 3, Supplementary Table 4). Overall, we found large trade-offs among different ecosystem services stemming from the three development pathways (Fig. 2).

High climate change significantly impaired ecosystem service provisioning (one-sample t-test, $P < 0.05$, Fig. 2, Fig. 3). Under high climate change, the Human Development pathway did not reduce the negative impacts of climate change on a number of services, despite slight trends of increase for some provisioning services (one-sample t-test, $P > 0.05$; Fig. 2, Supplementary Table 4). The Reduced Footprint pathway also reduced negative impacts of climate change for almost all services, and increased services of water provision, water and flood regulation and soil erosion and nutrient control when compared to states of high climate change alone (one-sample t-test, $P > 0.05$; Fig. 2, Supplementary Table 4). Despite of all alternative development pathways offsetting the impacts of climate change on all ecosystem services (one-sample t-test, for all scenarios $P > 0.05$), only Nature-based Solutions converted negative mean values into positive trends. It was most effective for biodiversity and habitat-related services, reducing extreme climate risks and turning it to positive effects (Fig. 2, Supplementary Table 3). Human Development, Reduced Footprint and Nature-based Solutions significantly reduced risks for coastal protection and water and flood regulation (GLMM, $P < 0.01$ under all pathways; Fig. 2, Supplementary Table 5). Overall, under high climate change conditions, for food/crop provision and raw materials provision, the pathway with the most magnitude of difference was Human Development; for water provision and soil erosion and nutrient control was Reduced Footprint; and for coastal protection, water and flood regulation, cultural services and biodiversity and habitat-related was Nature-based Solutions.

Under low climate change, the development pathways showed similar effects. Human Development reduced negative impacts for most ecosystem services except for carbon sequestration and coastal protection (one-sample t-test, $P > 0.05$; Fig. 2, Supplementary Table 4). It was able to increase all provisioning services, reducing risks for food/crop, raw materials and water provision. Reduced Footprint effectively buffered negative impacts on water provision, food/crop provision and biodiversity and habitat-related services (one-sample t-test, $P > 0.05$; Fig. 2, Supplementary Table 4). Nature-based Solutions effectively reduced negative effects and increased provision of all services, except water and flood regulation (one-sample t-test, $P > 0.05$; Fig. 2, Supplementary Table 4). It was especially effective for food/crop production and carbon sequestration. The pathways had significantly different effects on risks over coastal protection, where Human Development worsened risks, Reduced Footprint had no effect over risks and Nature-



(caption on next page)

Fig. 3. The impact of development pathways under different climatic contexts and its drivers of change. Mean effects of climate change alone are compared to effects of climate change with each alternative pathway. (a) The effect of three different development pathways to revert the negative impacts stemming from climate change on nine ecosystem services (for a detailed description of the pathways and ecosystem service definitions refer to Methods and Supplementary Table 2). High climate change corresponds to a state where climate change is not addressed and low climate change corresponds to a state where climate mitigation is implemented, leading to warming levels of above and below 2 °C in relation to pre-industrial levels, respectively (IPCC 2018). Decreases and increases are shown in negative and positive values, respectively. (b) Quantity of effect sizes on each of the drivers of change for each pathway. Adaptive potential can be accessed by evaluating as closer to zero the response is (i.e. non-significant results in the one-sample t-test). Results indicate that although there is great variance within responses to these strategies, Nature-based Solutions present the greater adaptive potential.

based Solutions increased services from −0.24 to 0.29 (Mean effect), respectively (GLMM, $P < 0.01$ under all pathways; Fig. 2, Supplementary Table 5). Overall, under low climate change, for raw materials and water and flood regulation the pathway with the most magnitude of the difference was Human Development, for biodiversity and habitat-related was Reduced Footprint and for all the other services was Nature-based Solutions, increasing food/crop provision, water provision, carbon sequestration and for coastal protection.

The impact of development pathways on all ecosystem services was driven mainly by changes in policy/management and urbanisation (Fig. 3). Direct interventions on nature, either exploitative or protective, were the drivers less represented in the literature. Biodiversity and habitat-related services were mostly driven by policy/management and changes in agricultural intensity. Coastal protection services were driven by changes on urbanisation (Fig. 3).

In the absence of climate change, the development pathways revealed different trade-offs (Supplementary Fig. 2, Supplementary Table 6) and were influenced by other drivers of change (Supplementary Fig. 3). For most ecosystem services, the Human Development pathway produced adverse effects, Reduced Footprint had null or slightly positive outcomes and Nature-based Solutions produced great positive effects, with the exception of raw materials provision that showed the opposite pattern (Supplementary Fig. 2). See supplementary material for further analysis of results and discussion of development pathways in the absence of climate change.

4. Discussion

Climate change severely impacted all ecosystem services. Considerable negative impacts are predicted if climate change remains unchecked, but the benefits of climate mitigation are noteworthy. The implementation of development pathways was a valuable strategy for climate change adaptation and to safeguard ecosystem services. However, we show the context-dependency of these impacts, which are mostly associated with ecosystem services' specificities. Thus, the choice of a development pathway should be established considering its potential impacts on strategic ecosystem services under low and high climate change conditions, observing stakeholders needs. Undeniably, Nature-based Solutions have the most potential to revert climate risks and increase multiple services despite high climate change conditions, thus increasing the natural and human system's resilience as a whole. We also found adaptive potential in Human Development and Reduced Footprint pathways, but these come with clear trade-offs. Identifying the risks and opportunities in the coming years is imperative for humankind to cope with a changing climate.

Our analysis of the trends in scientific literature warns that climate change will likely lead to a fate of substantial losses of ecosystem services. If we remain in a state of climatic recklessness, many ecosystem services might be depleted, highlighting the urgency of climate action (corroborating previous studies e.g. IPCC 2018, Lenton et al. 2019). Mitigation successfully buffered the impacts of high climate change for all ecosystem services, substantially reducing risks from climate change alone in the future. However, even under low climate change we are not exempt from losses (Nunez et al. 2019), so the pursuit of adaptive pathways is needed to ensure ecosystem service provisioning. Climate mitigation buys valuable time for society to adapt, and in turn, under low climate change, adaptive pathways produce even greater benefits (IPCC 2018). We reinforce that both mitigation and adaptation must be implemented concomitantly to ensure ecosystem services' persistence and safeguard the needs of future generations (Carter et al., 2018a).

4.1. *Trade-offs on the adaptive potential of development pathways*

Overall, the pursuit of each different adaptive pathway revealed different trade-offs in ecosystem services under climate change. The Human Development pathway shows benefits for provisioning services, although at the expense of all others. It has excellent adaptive potential by securing the extraction of immediate goods from nature in the form of food and water for consumption and raw products to support livelihoods (Foley et al. 2005), which otherwise could be depleted by climate change. The pursuit of the Human Development pathway can provide benefits directly related to societal needs, such as the Sustainable Development Goals of hunger and poverty eradication and economic growth (Wood et al. 2018). Indeed, food security is predicted to be one of the biggest societal challenges for a future with increased population worldwide (Smith et al. 2013). However, due to the extensive exploitation of land to obtain such direct goods, other essential ecosystem services can be compromised (e.g. Foley et al. 2005). Our results support the established trade-offs between food production and other provisioning services and other critical ecosystem services, such as habitat-related and regulating services (McElwee et al. 2020).

We have shown that an adaptive pathway to secure ecosystem services in a changing climate does not need to oppose human developmental needs (de Groot et al. 2010). At the same time, our results corroborate other studies showing that overexploitation of nature aiming at economic development is not the only pathway that can help achieve societal goals (McElwee et al. 2020). Nature-based Solutions also effectively reduced risks for provisioning services under high climate change, and under low climate change even increased its provision. Direct comparisons of Nature-based Solutions and alternative land-use interventions are still lacking in the literature (Chausson et al. 2020, Jones et al. 2012), but may prove to be valuable assets to mainstream such pathways. Nature-based Solutions proved not only to be the pathway with greater adaptive potential by minimising trade-offs, but also promotes synergies, as it concomitantly increases most ecosystem services (Cohen-Shacham et al. 2016), which can favour the achievement of the sustainability agenda (Pires et al. 2021).

There is adaptive potential even in pathways that are not based on over-exploitation of goods or preclude explicit nature conservation. Reduced Footprint, in particular, effectively reduced climatic risks and increased many services even under high climate change. Urban expansion is predicted in a future world with increased population size (Chen et al. 2020), however, we found great benefits in reducing the footprint of urbanisation. Although cities are usually perceived as intensifiers of climate change, they are also a 'fruitful terrain' for climate adaptation (Egerer et al. 2021), especially considering that the majority of landscapes is cemented, thus susceptible to many climatic hazards such as floods and heat-islands (Carter, 2018b, Manes and Pires 2022).

Lastly, the implementation of different development pathways was not always effective as a climate change adaptation strategy. We found that both Human Development and Reduced Footprint pathways had worse effects on carbon sequestration than climate change alone. Thus, to revert risks for carbon sequestration in a changing climate (Zhao et al., 2020), we must implement Nature-based Solutions (Bastin et al.

2019, Bustamante et al. 2019, Mackey et al., 2020, Roberts et al. 2017). Contrastingly, water and flood regulation was the only ecosystem service that Nature-based Solutions were unable to directly increase under mitigated climate change. The tighter relationship of water-related services with climate-induced phenomena (e.g. precipitation, floods, drought, extreme events) renders a complex interaction between the water cycle and climate change. For example, whereas nature restoration can lead to an immediate reduction of water availability due to increases in evapotranspiration rates (even on large spatial and temporal scales; Filoso et al. 2017), it is known to prevent floods (Manes and Pires 2022) and increase water quality in the longer term (Ferreira et al., 2018). Future studies should consider all aspects of the relationship between Nature-based Solutions, climate change and water to understand how it can affect water-related services. Thus, studies that aim to prioritize areas for Nature-based Solutions considering their complex interactions can further contribute to its successful implementation, especially facing uncertain climate futures (e.g. Farjalla et al., 2021; Manes and Pires, 2022).

4.2. Nature-based Solutions as the most promising strategy

By harnessing nature to solve societal problems, the adaptive potential of Nature-based Solutions is undeniable (Jones et al. 2012, Chausson et al. 2020). First, we confirmed that the actions associated with Nature-based Solutions effectively counteract climate change risks to ecosystem services persistence. These actions were successful even in a state of climatic recklessness that led to high climate change conditions. Although Nature-based Solutions cannot be considered as substitutes for urgent mitigation efforts (Seddon et al. 2021), they are vital in a future with delayed climate action where it is no longer possible to keep warming within the $<2\ ^{\circ}C$ goal. This is a crucial finding, given that even if all countries successfully deliver all greenhouse gas emission cutbacks promised in the Paris Agreement (UNFCCC 2015), we would still not reach the $2\ ^{\circ}C$ goal (UNEP 2019). Therefore, Nature-based Solutions are a required adaptation actions, whilst also usually capable of further promoting mitigation through carbon sequestration, lessening the need for adaptation itself (Cohen-Shacham et al. 2016, Griscom et al. 2017, Bustamante et al. 2019).

Second, beyond reducing risks, Nature-based Solutions were able to increase ecosystem services in the future, even under high climate change. Among the adaptive pathways analysed here, Nature-based Solutions was the one with the greatest magnitude of increases in ecosystem services across all groups (provisioning, regulating, cultural or supporting) and reduced trade-offs between them. Even though there is a lack of studies assessing Nature-based Solutions through direct interventions on nature, we found a great potential in policy and management towards sustainability (e.g. Rezende et al. 2018, Pires et al. 2017). Because it enhances the yield of ecosystem services to humans, Nature-based Solutions configure a ‘no regrets’ strategy, solving the negative impacts of the climate crisis and improving nature’s contributions to people (Cohen-Shacham et al. 2016).

Finally, Nature-based Solutions allowed co-occurring increases in multiple services, contributing to ecosystem resilience as a whole, even under high climatic change. Such an adaptive pathway based on a positive proactive transformation of the landscape is commonly linked to reinforcing loops of co-benefits perceived by stakeholders (Fedele et al. 2018, IPBES 2019). Ultimately, Nature-based Solutions can holistically address the climate crisis while producing several co-occurring benefits and promoting societal sustainable development goals (Seddon et al. 2021, IPBES 2019). In this way, Nature-based Solutions can be considered the most climate-resilient development pathway (sensu IPCC 2018).

4.3. Finding positive feedbacks to accelerate climate adaptation

The avoided loss of ecosystem services is *per se* beneficial in terms of climate adaptation. However, some ecosystem services can be considered particularly valuable in the context of future climate adaptation. Services that are likely to persist under change, or transform into other benefits, or even services that were not previously present but arise after change, are known as ‘climate adaptation services’ or ‘nature’s contribution to adaptation’ (Jones et al. 2012, Cohen-Shacham et al. 2016, Colloff et al. 2020, Lavorel et al. 2019). These services have intrinsic ecological mechanisms that allow them to still provide benefits even in a state of change, helping society cope with new climatic conditions (Lavorel et al. 2015). This is especially evident for regulating and supporting services that have a critical role in buffering ecosystems against climate change (Lavorel et al. 2015). Some of these climate adaptation services might even prove to be more valuable under future climates than nowadays, such as the ones related to known climatic risks that are predicted to be exacerbated in the future (e.g., flood prevention; Colloff et al. 2016, Manes and Pires 2022). Identifying and safeguarding essential services that will have a prominent role in a future under climate change acts as an insurance policy (i.e. ‘no regrets’) and avoids maladaptation (Colloff et al. 2020). Coastal protection perfectly illustrates these cumulative benefits derived from enhanced feedback of climate adaptation services: the pursuit of a development pathway that leads to avoided loss of ecosystem services, including coastal protection, is adaptive; but in turn, coastal protection has the perk of further reducing other consequences of climate change, such as promoting ecosystem-based disaster risk reductions against sea-level rise (Arkema et al. 2013, Roberts et al. 2017). By pursuing development pathways that enhance such adaptation services we ensure that their feedback of adaptation benefits are perpetuated (Jones et al. 2012). Our review highlights that Nature-based Solutions were the only pathway that was able to reduce risks on coastal environments and increase coastal protection (Arkema et al. 2013, Temmerman et al. 2013).

4.4. Defining a global strategy to promote nature’s benefits to people under climate change

Our literature review reveals many gaps in studies of climate change impacts over ecosystem services, and precisely due to such gaps our study is bound by key limitations. The disproportionate amount of studies focusing on Human Development pathways shows that there is widespread concern about the current trajectory humanity is pursuing, although assessments of alternative options are lacking. Further studies on the adaptive potential of alternative pathways are needed to strengthen confidence on such approaches. The literature on Nature-based Solutions shows very high agreement on its potential to safeguard nature, but it is still scarce and only depicted in the northern hemisphere, possibly because of the novelty of the concept. Developing countries in the Tropics, however, are where Nature-based Solutions are most needed due to their deforestation trends and socio-economic vulnerability (Benayas et al. 2009). In fact, the majority of countries lacked any estimate of impact, especially in less-developed nations. The dominance of English is substantial in any scientific field, and could be a source of bias for worldwide meta-analysis, including our own. Indeed, the scientific literature on the effects of climate change in ecosystem services is still centred on the global north, especially on the United States, hindering regional prioritisations (Runting et al. 2017). Actions must consider the knowledge gaps we currently face, and thus, further studies on key areas are needed to provide a more comprehensive analysis of risk and regional adaptive potential of development pathways and country-based policies (Manes et al. 2022, Pires et al. 2021).

Most studies assessed here were based on policy or management strategies, highlighting the importance and usefulness of a foremost change in attitude towards our relationship with nature. Well-established policy is essential to achieve societal goals (McElwee et al. 2020). Ecosystem services provide benefits that encompass all aspects of human life and well-being (Haines-Young & Potschin 2010), and are the foundation to meet societal goals such as the Sustainable Development

Goals (Wood et al. 2018, Anderson et al., 2019, Pires et al. 2021). Pondering different policy and management strategies allows decision-makers to better understand viable choices that enhance synergies between ecosystem services and sustainable development goals (McElwee et al. 2020, Pires et al. 2021).

Land interventions based on policy are particularly important drivers of climate action and adaptation (Rezende et al. 2018, Carter et al., 2018a). The relationship between climate change, adaptive pathways and ecosystem services must be mainstreamed into global and regional policies to increase their reach (Runting et al. 2017, Guerry et al. 2015, Di Gregorio et al. 2017). For example, Nature-based Solutions have been explicitly referenced in the Paris Agreement as contributors to both mitigation and adaptation, increasing the adaptive capacity of systems (Seddon et al. 2019). In fact, they are present on two-thirds of Nationally Determined Contributions in which countries rely upon to fulfil their pledges, emphasising the governments' global recognition of its potential (Seddon et al. 2019, Seddon et al. 2020, Grassi et al. 2017). Precisely, almost all of the poorest and least-developed nations declared that they will rely on must-needed Nature-based Solutions to adapt to climate change (Seddon et al. 2020). As we have shown here, however, significant literature gaps on its potential on such nations may hinder effectiveness. As a result, most nations merely outlined the use of Nature-based Solutions, with no information on how to implement it (Seddon et al. 2020). Efforts to assess the adaptive potential of such actions, like the one done here, are needed to inform decision-makers. The Paris Agreement was a vital policy landmark for climate action, but more ambitious efforts must be taken, especially those related to nature interventions. The Aichi Targets established by the Convention on Biological Diversity have not been achieved by 2020, and surprisingly for some elements we are further away from the target compared to the starting point (CBD 2020). Despite failure to meet this biodiversity agenda, it has been suggested that the coupling with the climate and sustainability agendas can help to design new targets for the coming years (CBD 2020). In this sense, the Nature-based Solutions must be the foundation of the Post-2020 Global Biodiversity Framework (CBD 2020), where ambitious efforts must be made to implement integrated multiple-linked goals and minimize trade-offs (Díaz et al. 2020). It will be critical to put mitigation and adaptation side-by-side to guarantee the fulfilment of climate agendas, which raises expectations for upcoming meetings to address climate change worldwide, such as the recent COP26 Climate Change Conference in Glasgow.

5. Conclusion

Climate change is expected to be one of the greatest threats to ecosystem services' integrity and stability, with possible direct and indirect impacts to society and human well-being. Our results confirm that climate change will potentially deplete many ecosystem services. Although mitigation benefits were noteworthy, they were not sufficient to halt losses in all types of ecosystem services analysed. Still, mitigation is urgently needed to reduce climate change risks and to increase the adaptation potential of the development pathways. All three development pathways analyzed here potentially buffered or even restituted ecosystem services against adverse impacts of climate change. The pursuit of such adaptive pathways is critical to ensure the flow of benefits from nature to people in face of climate change, especially when safeguarding climate adaptation services. Climate adaptation services, such as coastal protection, are critical for a no-regrets adaptation in an uncertain future, as they reinforce adaptation feedbacks. We suggest that focus should be given to identifying and perpetuating these nature's contributions to accelerate adaptation. We also reinforce the existence of critical trade-offs across ecosystem services in different pathways, and thus, the best-choice is contingent on stakeholders' needs. We conclude that Nature-based Solutions proved to be the best pathway to promote adaptation and safeguard ecosystem services, being able to secure and increase multiple co-occurring benefits even under unchecked climate change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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