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Review

The biodiversity-climate-food nexus: Illustrating challenges and solutions using the Green Shoots framework

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SUMMARY

Responding to the twin challenges of climate change and biodiversity loss is critical but so is avoiding any unintended consequences of these responses for other sustainability goals such as food security. Here, we explore synergies and trade-offs across the biodiversity-climate-food nexus through the recently developed Green Shoots framework. This approach highlights how different response options (dietary change, sustainable food production and fisheries, afforestation/reforestation, and bioenergy) can have multiple co-benefits, although some can also pose risks to biodiversity, climate change, or food security. Integrated responses are needed, but ultimately, success depends on how effectively they are implemented, and not on the type of response option per se. Society is at a critical juncture for the sustainability of most natural and food systems with today's choices affecting tomorrow's outcomes, and the Green Shoots provide an approach to inform these choices.

INTRODUCTION

Anthropogenic greenhouse gas emissions have resulted in global mean warming of 1.2°C above the pre-industrial period, with emissions increasing every year. Considering the remaining carbon budget, the 1.5°C target put forward in the Paris Agreement is likely no longer achievable.[1] Humanity is thus on a path to levels of warming considered to be dangerous anthropogenic interference with the climate system,[2] nullifying the primary objective of the United Nations Framework Convention on Climate Change (UNFCCC). Concurrently, more species than ever before are threatened with extinction from anthropogenic causes, two-thirds of the world's ocean and three-quarters of the ice-free land area are under direct anthropogenic use at different levels of intensity, and between one and six billion ha of land may be severely degraded.[3–5] Degradation is also widely identified in many marine ecosystems.[6,7] This direct use of land and seas is dominated by the need to feed the world's growing population. However, there are more than 800 million people undernourished today, with an increasing tendency,[8] making the supply of sufficient and nutritious food one of the foremost societal challenges. Clearly, humans are interfering dangerously not only with the climate system but also with socio-ecological systems.

The evidence is overwhelming that intact biodiversity and well-functioning ecosystems are required to mitigate (and adapt to) climate change and to achieve many of the Sustainable Development Goals (SDGs) beyond "life on land" and "life below water," including "zero hunger."[4,9,10] But likewise, biodiversity targets such as those of the Convention on Biological Diversity's (CBD's) Kunming-Montréal Global Biodiversity Framework can only be achieved if climate change is halted and feeding the world's population is decoupled from resource over-exploitation.[10–12] International and national climate and biodiversity policies increasingly acknowledge the close interdependencies of climate change and biodiversity loss and the need to closely align targets specified under the UNFCCC and CBD. Nevertheless, the agreed targets, but also the measures put in place to meet these targets, do not fully acknowledge the complex, non-linear interactions that exist in socio-ecological systems, thus risking failure because of environmental or societal trade-offs.[9,11,12]

Successful implementation of policy measures requires an integrated perspective that acknowledges the manifold direct and indirect drivers operating within the biodiversity-climate-food nexus.[13–15] We focus here on a range of widely discussed response options that either aim to contribute to climate change mitigation (especially through measures taken in land ecosystems) and/or underpin the supply of food. Response options include, for example, dietary change, sustainable food production, afforestation/reforestation, and bioenergy. They have been critically discussed previously regarding the co-benefits and negative side effects for biodiversity and human well-being (e.g.,[10,16,17] and references therein). Here, we use the available literature, and—where available—country statistics, to assess these options within the "Green Shoots" framework.[18] This framework was previously used to visualize the synergies and trade-offs arising from protected areas and their impacts on biodiversity, climate change mitigation, and food production.[18] Our previous work showed that area coverage targets such as protecting 30% of the marine and land surface, a core element of the Kunming-Montréal Global Biodiversity Framework, are meaningless unless accompanied by substantial improvements in protected-area effectiveness. Moreover, important differences in terrestrial and marine systems need to be recognized when setting and implementing protected-area targets, regarding both synergies and trade-offs with climate change mitigation and food production.[18] Here, we apply the Green Shoots visualization to a biodiversity-climate-food nexus perspective and explore a wider set of response options (beyond the initially investigated protected areas) that allow us to identify the opportunities that exist for achieving synergies across the nexus. The Green Shoots were inspired by the "burning embers" diagrams[19,20] of the Intergovernmental Panel on Climate Change but rather than communicating climate-change related risks, the Green Shoots emphasize options for solutions and contrast synergistic opportunities with actions that risk dangerous levels of anthropogenic interference in socio-ecological systems.

METHODS

The Nature's Green Shoots visualization with its solutions-oriented analytical framework aims to identify possible sets of actions toward achieving sustainability objectives in the use of natural resources, as well as positive synergies but also trade-offs that may be associated with these actions. The Green Shoots are represented as a 2D surface that contrasts a response option to address a sustainability challenge (here, biodiversity loss, climate change, and hunger) with the effectiveness with which that option is implemented. A detailed description of the method is provided in Arneth et al.[18] Briefly, a color scale from gray (a delay of an action, or even the action itself, is harmful) to green (action has clear benefits) identifies the solutions space. Responses of biodiversity, climate, or food production to an intervention can be linear or non-linear (for example, due to feedbacks in socio-ecological systems), and hence the color transitions from gray to green can also be linear or non-linear. Each Green Shoot diagram was developed in a separate worksheet (see the examples in Data S1, which is provided in the supplemental information). In each of the diagrams, the full color-range from dark gray to dark green is used, i.e., the implemented actions result in maximum unfavorable or favorable outcomes, which facilitates qualitative comparison between the Green Shoots. In these worksheets, the darkest green and gray shades correspond to values of −100 and +100, which enables subsequent re-drawing and smoothing of the surface of the Green Shoots (see Arneth et al.[18] for more details).

The assessment of the benefits or disadvantages arising from an intervention and hence also the choice of where the color transitions lie on the Shoots diagrams requires expert judgment, based on a review and evaluation of the published scientific literature. In some cases, the placement of the color transitions can also be based on available statistical data. For instance, in the analysis presented in this review, the impact of changes in (agricultural) food consumption and production was assessed with support from country-based data (see sub-sections "food production on land" and "(agricultural) food consumption" below). The vertical dimension (*y* axis) of the Green Shoots represents possible interventions that relate to policy targets and related indicators. Its scale ranges from none (or a very small) realization of an intervention to a maximum value, expressed in %. The solutions perspective of the Green Shoots diagrams also requires a second dimension (here plotted along the *x* axes), which captures the effectiveness of implementation. The level of uncertainty in color attribution increases with departure from current levels. Figure 1 provides a "generic" example of a Green Shoot as an illustration for how these should be read. The arrows and numbers on each Shoot refer the reader to concrete examples that we discuss in the respective sections in the context of each response option; these examples tend to be independent from one another.

We explore direct climate change mitigation measures (growth of bioenergy crops, expansion of area under forest, reduction of greenhouse gas emissions from agriculture), the impacts of fisheries, and dietary changes on biodiversity, climate, and food supply. These measures have been debated for many years regarding how well they address current unsustainable land and sea use, in particular (for the land-based measures) with respect to their potential to reduce the global "land-squeeze."[21] They have featured prominently in assessment reports by the IPCC (e.g., 2019[5] and 2022[22,23]) and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES; e.g., IPBES, 2019,[4] and McElwee et al.[24]) and a joint IPCC-IPBES workshop.[9,17,25,26] The main outcomes of these reports and the literature that underpins them, plus more recent literature and some country-level statistics, are the basis for this paper, and the Green Shoots visualizations (presented in Figures 2 and 3; see also supplemental information, Tables S1.1–S1.5).

Figures 2 and 3 are based on the templates provided in Data S1, which show the assumptions made for the transitions. The surfaces created in these worksheets were replotted and smoothed using R 4.3.1 packages sp, gstat, ggplot2, and automap using the *autokriege* and *kriege* (for Figure 2D, climate, and Figure 3B, climate) functions. The interpretation of the impact of different solutions is done here implicitly for present-day conditions (i.e., not considering future socio-economic changes) and in the global context, while recognizing that synergies and trade-offs arising from a response option will differ between regions and geographic scales. In principle, the spreadsheet-based approach also allows for a wider set of variables to be explored, including those at the regional scale, or for multiple socio-economic and climate change scenarios. Biodiversity is intended to cover all facets of biodiversity, but most of the cited

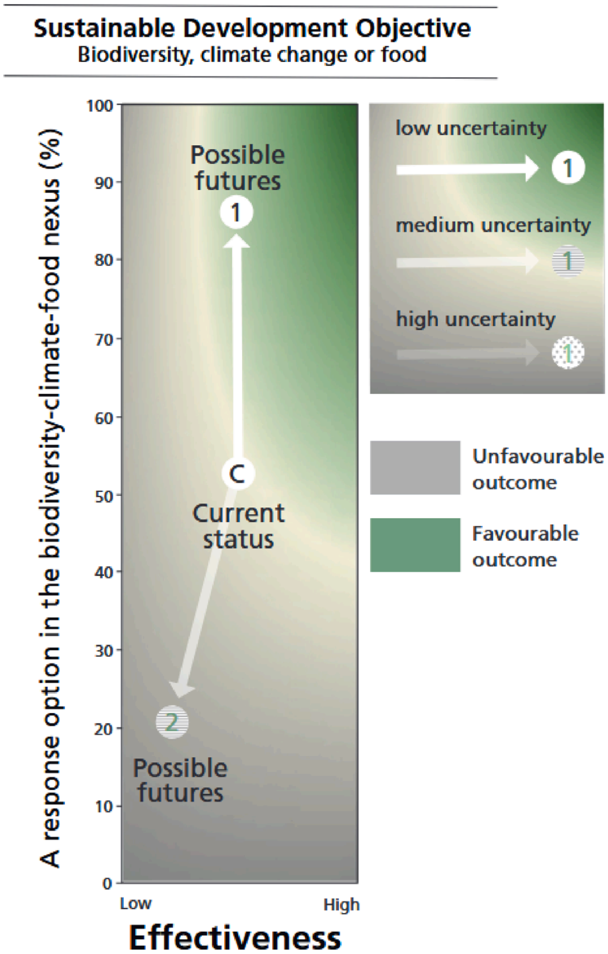

Figure 1. Green Shoots visualization

The green-to-gray color scale was chosen to illustrate overall favorable (green) or unfavorable (gray) impact a response option would have for sustainability challenges (here: biodiversity, climate change mitigation, or food supply). The vertical dimension (*y* axis) represents the degree of implementation of the proposed option, typically varying between a minimum of 0% to implementing the intervention to a maximum of 100%. The horizontal dimension (*x* axis) ranges from low to high level of effectiveness with which the intervention is implemented, "low" and "high" corresponding typically to an index ranging from zero to one. The current status is indicated by the encircled "c" in the *x*-*y* space. Numbers (1, 2...) represent different possible futures (discussed in the text) that illustrate the impact a change in the magnitude of the intervention and/or its effectiveness would have (possible futures). The arrows are included to guide the eye from the current status to each of the possible futures. The location of color transitions (gray to green), i.e., the degree of intervention at which the response becomes favorable or unfavorable, is uncertain, indicated by the different shading of the arrows and background numbers. In this example, strengthening the response option at unchanged effectiveness would be favorable with low uncertainty. In contrast, a decline in both effectiveness and the response option itself (possible future case 2) would be unfavorable, but with medium uncertainty regarding the strength and speed with which this would materialize. The Shoot example shown here can be combined with different panels to create one figure. Redrawn from Arneth et al.[18]

literature we used here refers to species diversity; climate change mitigation through actions in land ecosystems refers mainly to impacts on carbon pools and uptake, although for agriculture some of the cited studies refer also to other greenhouse gas emissions; food relates to quantity of food produced or food protein consumed.[18]

Food production on land

Food production can be increased in two ways: through intensification (including technology changes) and through cropland area expansion.[27] We focused on data for the cropland sector, which integrates over food for direct human consumption and animal feed; given the greater trade-off between expansion of area and fertilizer use for cropland compared to pasture, intensity of production on pastures was not considered.

Cropland production intensification was estimated from national 5-year averages in fertilizer application rates from FAOSTAT for 2017–2021 (http://www.fao.org/faostat/en/#home). Fertilizer application rates are expected to correlate with other yield-enhancing factors such as pesticides and herbicides, irrigation, and mechanized land management. After excluding outliers, we normalized (0–1) for the *y* axis values between the minimum and maximum values of all countries, such that unity (expressed as 100%) would be the country currently with the highest fertilizer input rate.

National production efficiencies were used to define the *x* axis, as the attainable yield (1) minus the yield gap.[28] This approach is often used for assessing opportunities to increase the agricultural productivity or vice-versa to estimate the amount of in-efficiencies in a production system.[29]

Cropland area expansion as a percentage of the total national area of a country was quantified for the period 2000–2021 (http://www.fao.org/faostat/en/#home). Similar to the normalization of intensification values, we normalized cropland expansion between the minimum and maximum values of all countries to improve comparability across countries and between area expansion and intensification, with 0% expansion having a normalized value of 0.5.

For details of these estimates see the additional information provided in the supplemental information. The color scale set in Figures 2A and 2B draws on these and is further refined based on the literature review.

Fisheries

We focus here on marine capture fisheries, including both industrial and small-scale fisheries, which extract wild fish and invertebrate species from their natural environment. We chose to address the sustainability of fisheries' seafood production through their impact on marine biodiversity (i.e., fish biomass) and fishery yield (i.e., catch). The assessment is based on key scientific reports and papers (see Table S1.2) that use fishery data reconstruction, scientific survey data, meta-analyses as well as single stock assessments. In the marine Green Shoots, the vertical dimension represents the proportion of sustainably exploited stocks, a common indicator (e.g., Shin et al.[30]) calculated to track whether "the impacts of fisheries on stocks, species, and ecosystems are within safe ecological limits" (Aichi Target 6 of the CBD), and whether fish stocks are restored "at least to levels that can produce maximum sustainable yield" (SDG 14.4). A stock is considered sustainably fished when fishing mortality (F) is kept below a level that produces the maximum sustainable yield (F_{MSY}). The vertical dimension is scaled between 0 (none of the fish stocks are sustainably exploited) to 1 (all stocks are sustainably exploited). The horizontal dimension (*x* axis) provides a measure of the effectiveness of fisheries management. We chose to reflect the efficiency in combatting illegal, unreported, and unregulated (IUU) fisheries, as the high proportion of IUU fishing is a main driver of overexploitation and stands in the way of efforts to rebuild depleted stocks.[31] Preventing, deterring, and eliminating IUU fishing is the main objective of the FAO Agreement on Port State Measures, a target of the UN SDG 14.4 and relates also to target 5 of the CBD GBF. The *x* axis is scaled between 0 (minimum effectiveness, corresponding to the upper estimate of IUU fishing risk index) and 1 (lower estimate of IUU fishing risk index).[32] Details of the method are provided in the supplemental information. The color scale set in Figure 2C draws on these and is further refined based on our literature review.

(Agricultural) food consumption

Food consumption was analyzed across a two-dimensional surface representing the fraction of plant-based foods in the diet on the *y* axis and a metric of consumer efficiency on the *x* axis (see Figure S3). Points on this surface represent food consumption patterns in terms of quantity and types of foods. Consumption efficiency is calculated as a required average per capita intake of 52 g protein/day[33,34] divided by an average per capita food protein supplied (comprising food eaten as well as discarded food waste), using data from FAOSTAT[35] for individual countries. The term "effectiveness" is used across all Green Shoots' horizontal dimensions and was also applied in the context of food consumption since efficient processes contribute significantly to effectiveness. A consumption efficiency of 1 (100%) implies the food supply exactly provides the required protein to meet nutritional requirements for the whole population if equitably distributed and with no discarded food. A value of less than 100% indicates on average an oversupply of food to the consumer, in comparison to nutritional requirements. This could be either in the form of consumer food losses or an individual's over-consumption, given that overeating is a form of food waste.[33,36] Values of consumption efficiencies above 1 (or 100%) indicate insufficient supply of protein, while a value of 100% (or below) can also represent a case where food is not equitably distributed, and potentially including undernourishment for some. To address this, adjusted efficiencies were calculated based on FAO data for the number of people undernourished per country.[37]

The vertical dimension represents the percentage of protein from plant-based foods in a countries' average diet. Commodity protein contents were obtained from FAO food supply,[35] with a calculated range of 30% to >90% plotted as an index (0–1). For details on these estimates see the additional information provided in the supplemental information. The color scale set in Figure 2D draws on these and is further refined based on the literature review.

Afforestation/reforestation

The *y* axis was scaled between 0 (complete deforestation) and 1 (maximum natural forest area, 50–55 km^2 [27,38]). Effectiveness was assessed based on the degree of naturalness of the forest, with 0 (low) being monoculture plantation forests (which could be native or non-native species) and 1 (high) being a natural species and age-cohort mix without or with very little human intervention. The assessment was done based on a review of the literature, with additional information provided in Table S1.4 in the supplemental information.

Bioenergy

Bioenergy crops are typically classified as either 1st or 2nd generation, with 2nd-generation lignocellulosic crops such as *Miscanthus* or short-rotation coppice. Second-generation bioenergy is considered to be much higher yielding with fewer input requirements,[39,40] such that "low" at the *x* axis corresponds to all bioenergy being 1st-generation bioenergy (e.g., maize, but also wood collected from forests) and "high" corresponds to all bioenergy being provided as dedicated 2nd generation. The vertical dimension is related to the contribution of bioenergy to the world's global primary energy production (which is presently ca. 640 EJ a^{-1}[41]). Given that most scenarios that explore the impact of bioenergy on other sustainability considerations other than climate change mitigation do not assume more than a maximum of ca. 300 EJ to be provided by bioenergy, we capped the *y* axis at 320 EJ a^{-1} (100%). The assessment was done based on a review of the literature, with additional information provided in Table S1.5 in the supplemental information.

EXPLORING SOLUTION OUTCOMES ACROSS THE BIODIVERSITY-CLIMATE-FOOD NEXUS

Food production on land

Since the early 1960s, global cropland area has expanded by nearly 7% (ca. 1.02 mio. km^2) and production has more than tripled to feed today's ca. 8 billion people.[4,5] In the recent two decades, the mean annual cropland expansion rate was 0.37% p.a., at a normalized production efficiency value of ca. 0.56 (Figure 2A, "c"; see supplemental information for further information). The supply of sufficient and nutritious food to all remains one of the foremost societal challenges.[8] This goal could in principle be achieved by further expanding agricultural land (Figure 2A, "1"), but the conversion of natural land into managed land together with agricultural intensification have severely reduced local biodiversity such that already now more than 70% of humans live in an environment in which the "planetary boundary" for relative species abundance has already been transgressed.[42] Given that many cropping systems are monocultures with a large degree of mechanization on homogeneous landscapes, further expansion of agricultural area is expected to add additional stress on biodiversity.[43,44] In addition, croplands typically have lower carbon content in vegetation and soils compared to the natural system they replace. Conversion of natural into agricultural systems causes annual CO_2 emissions of ca. 1.2 Gt a^{-1}[45] and has contributed 40% of the cumulative total global CO_2 emissions since 1850.[45] Cropland expansion without further biodiversity and carbon loss is considered unattainable[46] and not directly modulated by effectiveness (Figure 2A, "1" and "2"). Our visualization does not capture indirect effects, as effectiveness impacts the rate of necessary cropland expansion required to produce more food—and the negative effects on biodiversity and emissions from agricultural area expansion could be reduced by increasing production efficiency to compensate for the need for additional expansion. Likewise, while restoration of natural ecosystems at the expense of managed land is seen as an important aspect of biodiversity conservation, with co-benefits for climate change mitigation,[16] negative consequences for food supply (Figure 2A, "3") could only be avoided if enacted in parallel with other measures such as reducing food wastage or dietary changes (see section "(Agricultural) food consumption" and Figure 2D). Expanding cropland in areas of high production efficiency, with sufficient but no oversupply of e.g., agrochemical or irrigation-water use, could, however, come with rapid gains regarding global yields and food supply.[47]

Between 1985 and 2005, global yields rose by ca. 28%, of which ca. 20% were attributed to fertilizer application.[48] Increasing production intensity could be a much more promising route to reduce hunger and malnourishment than agricultural expansion if measures taken to do so would not interfere with other sustainability objectives in the biodiversity-food-climate nexus. Yet, at present, the world's food production system is far from such a trajectory. Inefficiencies in fertilizer application rates lead to over-fertilization, resulting in groundwater contamination, eutrophication of freshwater, and estuarine ecosystems, to the detriment of biodiversity within these ecosystems[49] (Figure 2B, "c"). The global mean fertilizer application rate is 150 kg/ha p.a. (weighted by crop area) or ca. 0.3 when normalized (see supplemental information). Pesticide use has increased by >80% over approximately the last three decades (https://www.fao.org/faostat/en/#home). Agriculture alone accounts for approximately 70% of global freshwater withdrawals—in some regions up to 95% (FAO 2017)—and is a major contributor to climate change. Aside from CO_2 emissions from agricultural expansion, management on existing croplands is a large source of N_2O and CH_4 emissions.[50,51] An unknown quantity is lost in addition as reactive N (such as NH_3 or NO_x), with additional climate impact through their contribution to the formation of tropospheric ozone or secondary organic aerosol.[50] Overall, agricultural production is responsible for 13%–31% of annual anthropogenic greenhouse gas (GHG) emissions (2010–2019;[22]), the food system's contribution as a whole (including transport and fertilizer production) amount to >25%[5] (Figure 2B, "c").

Increasing production efficiency by minimizing yield gaps is an important option to increase food supply without expanding croplands. At high efficiencies, fertilizer application rates of around 80–100 kg ha^{-1} a^{-1} globally (ca. 20% on *y* axis and assuming potash and phosphorus follow nitrogen fertilizer; Figure 2B, "1"), seems a realistic target to meet future food demands,[49] while substantially reducing impacts on biodiversity and GHG emissions. Over-fertilization is still prevalent in many regions (Zhang et al.[49]; Figure S1), with rates above 200 kg/ha/year in western countries, which can result in high yields but with associated biodiversity and climate consequences. In practice, very high fertilization rates can also be harmful to crops and contribute to acidification of soils or long-term declines in soil organic matter.[52,53] National data on toxic fertilizer application rates is lacking, but the FAOSTAT shows around the year 2000–2005, diminishing returns for yields, when application rates exceeded 300 kg/ha (Figure 2B, "3"). Moreover, a recent study[54] showed that some of the top crop-producing countries are still able to increase their yields despite lowering their fertilizer application rates, placing them among the countries with the highest fertilizer use efficiency worldwide (e.g., Denmark, France, Germany, and Austria; Figure 2B, "2"). This suggests that there is further room to lower fertilizer application rates while maintaining high outputs.

The size of the yield gap is partially related to the availability and efficient use of fertilizer but also reflects other factors such as irrigation, pesticides, technology, crop varieties, machinery, and knowledge.[55] These are to a large degree correlated. In order to close the yield gap, it is more important to apply inputs efficiently, rather than simply applying more. Thus, we imply for closing the yield gap an increase in intensity would not automatically have further benefits, while a variety of approaches to reduce overfertilization such as precision agriculture, adaptive farming practices, alternative farming systems (e.g., indoor farming), and crop breeding are powerful tools to reduce pressures on cropland expansion and thus reduce biodiversity loss and GHG emissions (Figure 2B, "1").[28,56,57]

Fisheries

Seafood is an important source of nutrients, not only for coastal populations but also for people living inland supported by increased transport, preservation, and refrigeration capacities.[58–60] Since the 1960s, the annual increase in seafood consumption (3.1% per year) has both exceeded that of human population growth (1.6% per year) and that of land-animal protein consumption (2.1% per year).[61] Today, the per-capita annual seafood consumption is on average 20.5 kg, providing 17% of the world population's intake of animal proteins.[59] Wild fisheries have provided the majority of food from the sea (70% in 2020),[58] even though recent data show that global aquaculture production surpassed that of capture fisheries in 2022, representing 51% of the total aquatic animal production,[62] in line with scenarios of mariculture.[59]

The latest FAO global assessment shows that the proportion of overexploited marine stocks (37.7%) has reached a historical record,[62] meaning that both marine biodiversity and fisheries' sustainability are threatened[63,64] (Figure 2C, "c"). Under current management effectiveness (IUU fishing risk index is 2.28 at global scale[32]), the transition between green and gray for fish biomass stands at about 75% of sustainably fished stocks, just below the current situation in the US (81% of sustainable fished stocks; NOAA[65]; Figure 2C, "1"; see also Data S1 in the supplemental information). This is still well below the situation in the 1970s when the first collapses in major fish stocks happened with only 10% of the fish stocks being overexploited (FAO Fishstat, http://www.fao.org/fishery/statistics/en)—at a time when the rate of increase in global fishing effort began to take off sharply and the decreasing catches per unit effort reached an inflexion point in many parts of the world.[66,67] In the Mediterranean Sea, for instance, the proportion of sustainably fished stocks is far below the global situation and very far from reaching the 75% transition level (Figure 2C, "2"). However, changes in management and fisheries regulation in the region have led to a very rapid shift toward more sustainable fishing, with the number of sustainably fished stocks jumping from 25% in 2018[68] to 42% in 2021.[69] A similar rate of change in the future would ensure the recovery of fish stocks in the region, which is currently one of the most overexploited in the world. It is worth noting that sustainable fishing can still negatively impact biodiversity: when stocks are exploited at F_{MSY}, their biomass is reduced to ca. 0.35–0.4 of their pristine biomass.[70] So the maximum biomass represented in the green shoot as the greenest corner (100% sustainably fished stocks and no IUU fishing; Figure 2C, "3") is still far from the pristine

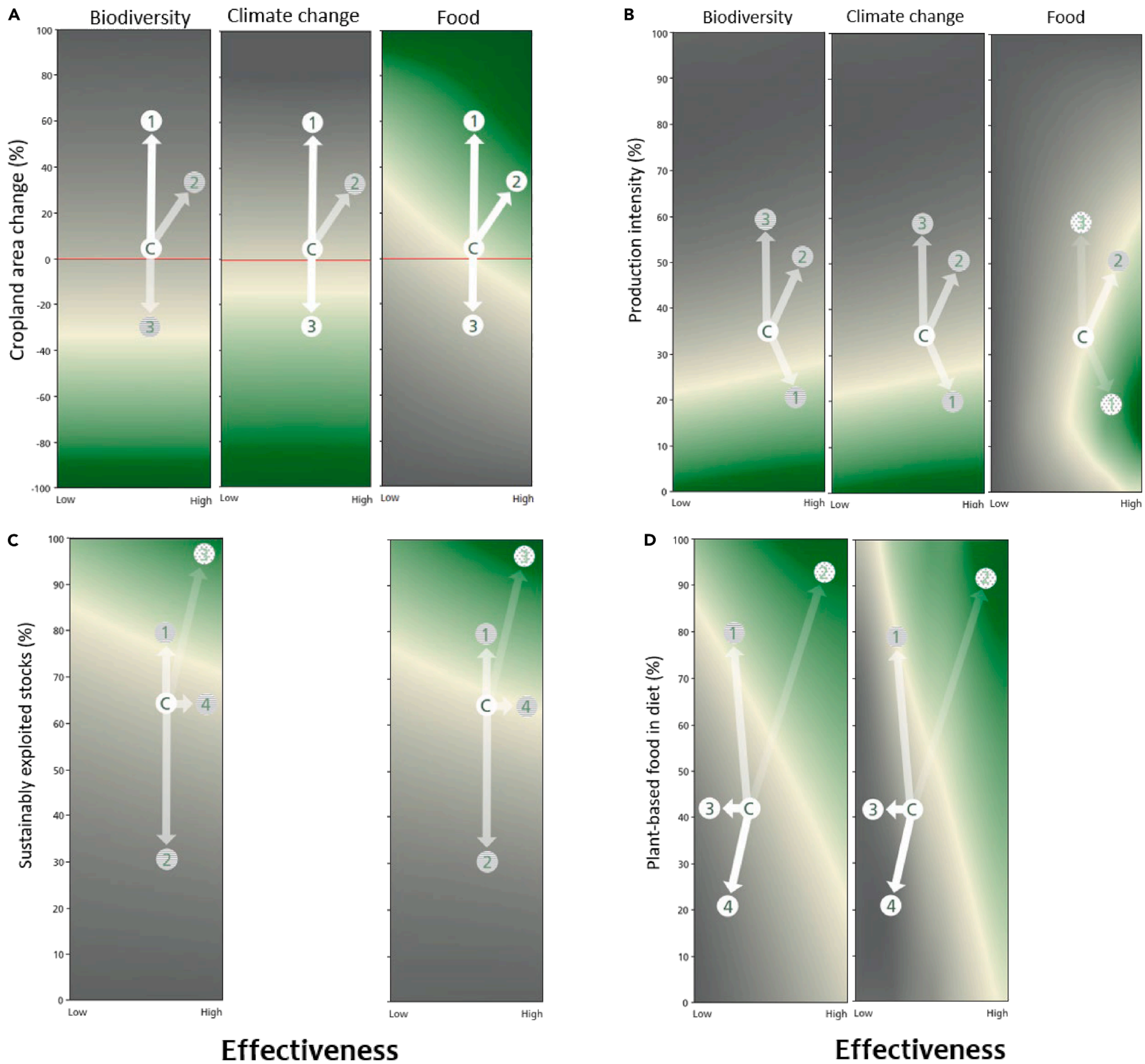

Figure 2. Food production and consumption patterns

(A) Impacts of cropland area change as indicator for conversion of natural into managed land; expressed as % change globally in 2021 since the year 2000. The red horizontal line highlights that in this case the vertical dimension changes from zero to positive (further cropland area expansion) and negative (illustrating cropland area decrease).

(B) Impacts of N-fertilizer application on cropland as indicator for intensification of production, normalized by the global mean of national fertilizer application rates.

For (A) and (B), national yield gap estimates are used as a measure of effectiveness plotted such that a value of 1 (high) corresponds to the case of zero yield gap (i.e., (1-yield gap)).

(C) Impacts of the proportion of sustainably exploited wild marine populations as an indicator for fishing pressure (*y* axis) and of the proportion of illegal, unreported, and unregulated fisheries as an indicator for management inefficiency (*x* axis). Impacts on fish biomass, as an important component of biodiversity and fishery yield, which is an important food source. Changes in sustainably exploited stocks of fish do not have a direct climate-change mitigation impact; therefore, this panel is missing in (C).

(D) Impacts of changes in consumer food and feed demand, indicated by animal protein in diet. Each metric was calculated across a two-dimensional surface of percentage of plant-based foods in the diet on the *y* axis (in terms of mass of protein intake) and a metric of consumer efficiency on the *x* axis, based on country-level information. Dietary changes do not directly impact food availability; therefore, this panel is missing in (D).

All panels: Labeling and color scale as in Figure 1. Further information: methods section, supplemental information, and Tables S1.1–S1.3.

biomass of fish. On the other hand, when targeting the maximum economic yield (MEY, which is sometimes adopted as the management target rather than the MSY, e.g., in Australia;[71]), the fish biomass is reduced less, to ca. 0.5–0.6 of their pristine biomass.[70] The biodiversity status could improve when IUU fishing decreases (management effectiveness increases; Figure 2C, "4"). Costello et al.[72] estimate that applying F_{MSY} to all stocks of conservation concern would increase fish biomass at 994.4 million tons (current biomass is estimated at 840.3 million tons in early 2010s). This represents an increase of 18.34%. Our calculations suggest that transitioning to all stocks sustainably fished and halting IUU fishing could potentially increase fish biomass by close to 37% (corresponding to maximum effectiveness and 100% stocks sustainably fished; Figure 2C, "3").

Regarding fishery yields, and hence the contribution to global food supply, under current management effectiveness (Figure 2C, "c") the transition between green and gray corresponds to the situation in the late 1980s (in 1987, total catches reached 78 million tons with 75.7% stocks sustainably fished [https://www.fao.org/fishery/en/resources]) where catches started to level off. On either side of this transition, we find the current situation of the United States with 81% of sustainably exploited stocks[65] Data S1 supplemental information and the global fisheries situation in 2021 with 62% of the exploited stocks within biologically sustainable levels (Figure 2C, "1"; see also Data S1 in the supplemental information).[62] IUU contributes to overexploitation.[32] Halting IUU (Figure 2C, "4") would allow to sustainably exploit more stocks and to increase yield. Costello et al.[72] show that reaching F_{MSY} would increase catches by 17% (this consolidates an earlier study by Ye et al.[73] estimating a yield increase of 16.5%), compared to the current situation. Our calculations estimate that we could then expect 36% more catch if 100% stocks were sustainably exploited and IUU halted (Figure 2C, "3").

Depending on the scenario, the catch for marine seafood may increase by between 36% and 74% by 2050 compared to current yields.[59] Target 6 of the CBD Strategic Plan for Biodiversity, the FAO Code of Conduct for Responsible Fisheries, and SDG 14.4 urge nations to stop overexploiting marine populations and put in place rebuilding strategies (100% sustainably exploited stocks). Such a strategy combined with halting IUU fishing would allow a substantial increase in both fisheries production and fish biomass in the sea (one estimate would be ca. 36%); this is particularly critical in the context of climate change with projections of up to ca. 20% decrease in fish biomass under high warming scenarios by the end of the century.[74]

(Agricultural) food consumption

Animal products, and especially ruminant meat, are more resource intensive to produce than plant-based foods, requiring more land and water, and are associated with higher rates of greenhouse gas (GHG) emissions.[75] Today's crop and pasture area together are approximately 50% of the ice-free land area, around 50% of this global agricultural area is used for feed production or grazing.[76] Approximately 25%–30% (around 7 million km^2) of the area used for grazing would also be suitable for growing food crops.[77] Country statistics rebased to the 0%–100% scale (see supplemental information) indicate that as a population weighted average globally (2021) 41.2% of the protein consumed is from plant-based foods (Figure 2D, "c"). This is notably lower than a diet recommended for healthy and sustainable consumption.[34] In addition to the too high and inequitable animal-protein consumption, a third (24%–40%) of the food commodities produced globally are lost or wasted on the way from the field to the consumer.[33,78,79] Likewise, consuming food in excess of nutritional requirements (i.e., over-eating) can be considered as a loss to the food system.[80] Using country statistics and rebasing to the 0–1 scale, the present-day (Figure 2D, "c") country-average efficiency was 22.3%, after also accounting for undernourishment (see supplemental information). Food waste and losses are thus another important factor when assessing consumption impacts in the food, climate, and biodiversity nexus.

An agricultural area of 25% of the ice-free land has been put forward as an area under use for which global biodiversity would not be affected negatively overall,[44,81] which is approximately the area needed to feed the world's population on a diet similar to the average food consumption of India.[82] Reduction in animal-protein overconsumption (mostly the western world) has been identified in numerous studies as a key factor in stopping biodiversity loss from further conversion of natural lands and making room for protected area for biodiversity conservation (Figure 2D, "1").[18,83–87] This includes, for instance, reducing the export of beef and of soy used as feed from Latin America and SE Asia predominantly into Europe, China, Russia, and the Middle East, which are a major driver of loss of tropical rainforests and savannahs.[88]

Halving animal-product intake through changes in animal-rich "Western diets" in combination with avoiding meat from producers with above-median GHG emissions was estimated to make available 21 million km^2 of agricultural land and reduce GHG emissions by nearly 5 $GtCO_2$-eq a^{-1}.[75] These estimates increase to up to 10 $GtCO_2$-eq a^{-1}, around a quarter of today's anthropogenic greenhouse gas emissions,[89] when vegetation carbon uptake is considered on converted agricultural land.[75] Here (following Alexander et al.[82]; see supplemental information) we calculated agricultural area to require only 7% of the ice-free land in a hypothetical scenario corresponding to a global vegan diet (and 100% consumer efficiency), which could make large areas available for ecosystem restoration and also other climate change mitigation measures (see, e.g., sections "afforestation/reforestation" and "bioenergy," below). A dietary shift toward less meat would also have large co-benefits for climate change mitigation[10,90] (Figure 2D, "1" and "2").

Animal grazing can, however, also benefit biodiversity locally by maintaining open landscapes. Especially at relatively low stocking density, grazed pastures and silvopastoral systems often are species rich[76,91] and store substantial amounts of carbon below ground.[92,93] Overall, studies show diverse impacts of low grazing intensity on biodiversity, depending on the climatic environment, grazing species, and biodiversity indicator assessed.[94–96] In our assessment, we do not assume a lessening of the positive impact on biodiversity in a completely vegan world (Figure 2D, "2") but note that this assumption comes with very high uncertainty and may be too optimistic. Likewise, a notable change in global animal protein consumption could have regionally diverse spill-over effects via food and land prices, declining share of agriculture in countries' GDP, changes in food commodity trade, and economic consequences for non-food sectors that could reduce some of the positive outcomes, including for biodiversity and greenhouse gas emissions.[97] While a shift toward plant-based diets has substantial benefits for biodiversity and climate, the reduction in pressure on land is more rapid, as livestock production today is a higher percentage of agricultural land in comparison with the proportion of GHG emissions from the agricultural system. This gives rise, for example, to the differences in the slopes of lines of equal score between Figure 2D, "1" and "2."

More than 20% of the global crop area is used to produce food that is not eaten,[79] an area indicative for the detrimental impacts food losses and wastage have on biodiversity and the large GHG emissions associated with them. On-farm losses alone have been estimated as 16% of global agricultural-related GHG emissions.[98] Others state that if total GHG emissions from food waste—without accounting for emissions from land-use change—were attributed to one country, it would be the third largest emitter globally.[99] A recent analysis attributed nearly 50% of the total food system's GHG emissions to food loss and waste.[100] Food system losses from over-consumption of food may be of a similar magnitude as the losses from food thrown away by consumers.[33] Reducing the losses of foods by retailers and consumers (including over-consumption) jointly with a more healthy and equitable distribution of animal protein intake has the potential to provide a substantial reduction in the demands placed on agriculture and hence improve global sustainability (Figure 2D, "2").

Despite increasing public and media coverage on the health and environmental benefits of low-meat diets, per-capita meat consumption in countries such as the USA and Europe are relatively static and globally continue to rise, with higher incomes linked to greater total calorie and protein consumption and diets containing more animal products.[101–103] For meat over the coming decade, a global increase of 2% has been projected, with strong trends in middle-income countries.[103] Shifts toward consumption of poultry might reduce pressures on land to some degree, but projections also expect dairy production to be the fastest growing agricultural commodity.[103,104] Continuation of these trends toward the global population consuming a diet similar to today's average "Western" diets (e.g., supplemental information, Figure S3) would continue to drive land-use change and agricultural intensification with high agrochemical use, and hence GHG emissions and biodiversity loss, especially if such a trend would also be accompanied by high levels of food waste and over-consumption (Figure 2D, "3" and "4").

Afforestation/reforestation

Forests cover a remaining 40 (32–43) mio. km^2 of an estimated potential maximum natural cover of ca. 50–55 mio. km^2 (Figure 3A, "c").[27,38] Avoiding further forest deforestation is critical for climate regulation and for biodiversity.[105–107] Recent decades have seen the expansion of forest area in temperate regions while tropical deforestation continues.[27,108] The global vegetation carbon pool in forest biomass on today's forested land has been estimated as 68%–80% of its (non-harvested) maximum,[109] less than 40% of forest area contains forests older than 140 years[108] (Figure 3A, "c"). Given that forests provide habitat to a wide range of species, deforestation is a well-established cause of biodiversity loss (Figure 3A, "1"). Forest degradation (as a result of, e.g., replacing mixed-species forests by even-aged monocultures, selective logging, removal of dead wood) is an additional major driver, which is much less well documented (Figure 3A, "2").[110,111] Likewise, carbon losses associated with deforestation are large, additional losses from degradation (in regrowing but also in mature forests) are—as for biodiversity—under-studied, but potentially also considerable.[112,113] These effects are amplified by tree mortality in the wake of extreme weather events and their interactions with insects and fire.[114,115]

Restoring natural forests beyond today's areal coverage is expected to have a positive impact on biodiversity, in particular if natural regrowth is facilitated or when a mix of native tree species is planted (Figure 3A, "3").[116–119] But afforestation in principle can also take place in regions that naturally would have little woody cover, such as savannas or drained wetlands, which would destroy the local biodiversity in these ecosystems (Figure 3A, "4").[120–122] In addition, monoculture plantation forests have considerably lower biodiversity value than primary or secondary forests.[44] They can even be detrimental to biodiversity if a planted species becomes invasive.[123]

From a carbon cycle perspective, and even without considering area expansion, young forests typically have notable carbon uptake. Forests regrowing after clear-felling have been found to contribute around one-third of the annual forest carbon sink in 2001–2010,[108] while others studies imply that the sink in regrowing forests may be even larger.[108,124,125] Afforestation and reforestation are often considered cost-effective climate change mitigation options.[126] Projected future carbon uptake rates in some scenarios reach up to an additional annual uptake of around 3 Gt a^{-1}, a number would double today's entire global carbon sink on land. However, these projections are contingent on assumptions about large-scale forest area expansion[126,127] and do not consider the broader ecological roles of forest, risks to forests from climate change, or socio-economic constraints that could range from land ownership or availability of tree seedlings to short-comings in carbon markets.[115,128,129] By contrast to highly diverging impacts on biodiversity from natural vs. non-natural forests area expansion, differences in net carbon uptake and storage are smaller,[130] but intensive forest management or forests expanding into other carbon-rich ecosystems are much less efficient (or even negative) from a carbon cycle perspective compared to naturally regenerating forests (Figure 3A, "3" and "4").[119,131] Monoculture tree plantations are also particularly vulnerable to storms, fire, and pest outbreaks.[119] Grasslands store approximately 20% of the world's soil carbon, and contribute globally >20% to the total land carbon sink,[109,132] so replacement by forests carries large risks of severely misjudging the intended benefit for climate change mitigation. Biophysical surface exchange processes can lead to local cooling or warming, while forests' biogenic volatile organic carbon emissions interact with atmospheric chemistry in complex ways, which adds large uncertainty to forest-related climate change mitigation expectations.[50,133,134]

One of the most contentious issues of expanding forest area (whether for climate change mitigation or restoration or both) is related to competition with land used for food production. Having too little forests would likely have negative implications even though this would potentially provide more land for agriculture, buffering increasing calorific demands of a growing human population. But forests also provide habitat for pollinators[135,136] such that further loss of forest area would eventually be expected to affect food production negatively (Figure 3A, "1"

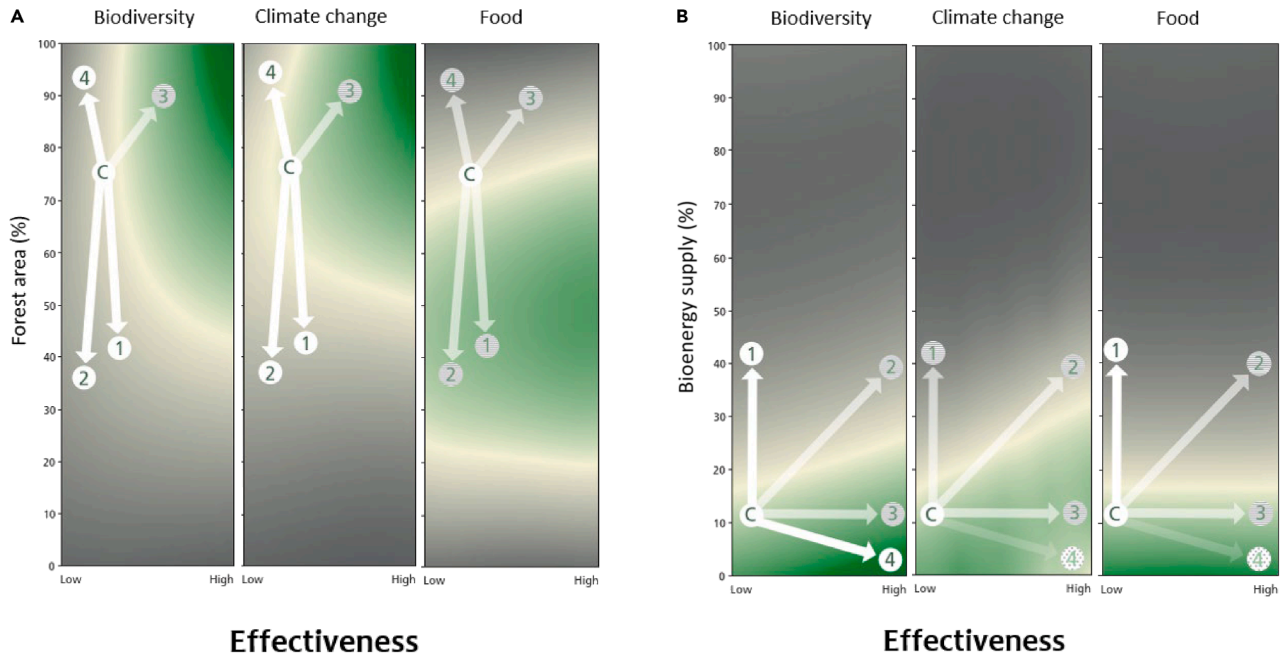

Figure 3. Forest area and bioenergy supply

(A) Impacts of climate-change mitigation through forest area expansion (expressed as % of potential forest cover); the degree of naturalness of forest composition is used to indicate effectiveness. Some scenarios in the published literature assume extending forest area beyond its estimated potential (i.e., afforesting savannahs). We do not include such a possibility in the graph.

(B) Impacts of climate-change mitigation through planting bioenergy crops. Impact is assessed here in relation to land carbon uptake and storage. Bioenergy is related to today's primary energy production. In most scenarios in the literature, the maximum bioenergy in the total energy mix explored is 300 EJ, which is nearly ca. 50% of today's global total. 100% therefore is equivalent to 320 EJ (see methods). Effectiveness is 1st- vs. 2nd-generation bioenergy.

Labeling and color scale as in Figure 1. Further information: supplemental information and Tables S1.4 and S1.5.

and "2"). In practice, a world without forests would be uninhabitable due to climate feedbacks. Forest area expansion at large scales will, however, compete with land for agricultural production, with little difference arising from the forest type (Figure 3A, "3" and "4").[137,138] Such competition for land would reduce crop production globally, unless compensated by further management intensification on existing agricultural land to enhance yields[10,126]—with associated GHG emissions—as well as increasing food prices.[138]

Bioenergy

Increasing reliance on bioenergy, with carbon capture and storage, is a fundamental characteristic of GHG emission trajectories that require CO_2 removal from the atmosphere to limit global warming to 2°C or below.[10,126,139] At present, bioenergy provides around 45 EJ a^{-1},[41] less than 10% of the total global energy demand of ca. 640 EJ a^{-1} (rescaled to 14% on our *y* axis). Only around 3–5 EJ a^{-1} is from dedicated energy crops[41,140] (Figure 3B, "c"). Most of the global bioenergy is still used in the form of traditional wood-fuel, of which up to one-third is harvested unsustainably and also combusted inefficiently.[41,106,140] The current situation is in stark contrast with some projections of future bioenergy supply that increase to well over 150 EJ a^{-1} in only a few decades.[126] In some projections, the necessary land area required to grow bioenergy crops is equivalent to up to 50% of today's cropland, which is why these projections are regarded as unsustainable from many environmental and societal perspectives.[10,126,128,141,142]

For strong climate change mitigation scenarios, the required expansion of land area for bioenergy crops was found to have similarly negative impacts on terrestrial biodiversity as with unmitigated climate change,[143,144] even for 2nd-generation bioenergy, due to a reduction in species' ranges and pressure on protected areas (Figure 3B, "1" and "2"). Agricultural intensification can reduce competition for land but is likely to be accompanied by substantial increases in agricultural water withdrawals, fertilizer use, organic soil C losses, nitrate leaching and N_2O emissions, with further ramifications for biodiversity and climate change (see, e.g., Figure 2B).

Lignocellulosic crops have generally larger yields than 1st-generation bioenergy crops[39] while requiring less fertilizer or irrigation inputs.[40] Moreover, perennial crops can also increase local habitat diversity,[145,146] which is why replacement of today's still mostly 1st-generation bioenergy by similar energetic returns of 2nd-generation bioenergy is considered a relative gain—although reducing the area used for bioenergy crops will overall be beneficial for biodiversity (Figure 3B, "3" and "4").

Policies that promote large-scale use of biomass for energy production are problematic since they tend to assume that biomass-based energy is per se carbon neutral.[147] In practice, the impact of bioenergy cropland expansion on carbon storage in ecosystems is highly uncertain. First-generation bioenergy requires substantial energy input to convert the harvested biomass into useable fuel, which greatly reduces its area-effectiveness[126] and contributes to large carbon losses resulting from land being converted into energy crops (or from indirect land-use changes associated with bioenergy cropland expansion; Figure 3B, "1").[147–149] But even for 2nd-generation bioenergy crops, a number of process-based ecosystem models have found that cumulative net carbon uptake rates over time were considerably lower, compared to bioenergy carbon uptake numbers calculated in integrated assessment models.[150–152] While the reasons for this discrepancy are not yet fully resolved, these studies raise doubt about how realistic some of the postulated mitigation potentials from bioenergy (together with carbon capture and storage) are in practice, given large area requirements also in 2nd-generation scenarios and when full ecosystem carbon cycling and legacy effects of land conversions are considered (Figure 3B, "2"). Still, at moderate levels, 2nd-generation bioenergy crops such as Miscanthus or woody short-rotation coppice have substantially lower impact compared with 1st generation bioenergy because of reduced fertilizer needs and a larger proportion of the aboveground biomass being used for energy production.[145,153] In field studies these crops have also been found to contribute to ecosystem carbon restoration and/or enhance habitat diversity compared to current bioenergy crops (Figure 3B, "3").[154] This is why complete absence of 2nd-generation bioenergy (if grown on cropland) could be even less favorable for ecosystem carbon balances (Figure 3B, "4") compared, for example, with a complete absence of 1st-generation bioenergy.[106,145,153,154]

Given that today cropland and intensive permanent pastures already cover nearly 20 mio. km^2 and extensive pastures on potential forested sites take up an additional ca. 9 mio. km^2, [27] the further conversion of substantial natural land area for growth of bioenergy crops must be regarded critical also from a food perspective. Attribution of bioenergy impacts on food prices is challenging and depends on the methodology applied, regions and period investigated, and type of bioenergy crop.[140,155] However, already for the first decade of the 21st century, the enhanced use of food crops for the production of bioenergy (e.g., from grain, oilseeds, or vegetable oil) has been estimated to contribute significantly (e.g., order 15%–30%) to observed food price increases, such as for US corn.[140] In simulations that include future expansion of bioenergy crops, food (and water) prices have been shown to increase notably, caused by multiple factors, such as carbon prices, enhanced costs of intensification (in studies that seek to restrict cropland expansion) or competition for land[127,156,157] (Figure 3B, "1" and "2"). Second-generation bioenergy should in principle have lower impacts because of higher yields and because lignocellulosic crops do not directly compete with food production. Nevertheless, enhanced use of non-food bioenergy crops will still compete for cropland area and hence affect food prices (Figure 3B, "2" and "3").[126,140] Both the price increases and impacts on human societies depend strongly on the underlying socioeconomic assumptions. Hasagewa et al.[158] pointed out that mitigation policies across a number of scenarios resulted in increases in food prices and risk of hunger compared to scenarios without carbon prices, even exceeding climate change impacts on food prices.

Overall, by applying EU renewable energy sustainability criteria globally, a 2nd-generation bioenergy potential of 88 EJ a^{-1} (28% on our *x* axis) has been estimated, with the authors cautioning that this may well be reduced to annually ca. 50 EJ a^{-1} depending on uncertainties related to future crop-yield growth.[159] Others have put forward around 60 EJ a^{-1} as a conservative estimate based on studies that restrict bioenergy crops to "marginal" land and exclude expansion into currently protected areas.[126] Relying on large amounts of bioenergy, which still underpins many climate change mitigation scenarios, will cause environmental and societal harm and interfere with the achievement of several other sustainable development objectives.[10,126,141,160]

TOWARD SUSTAINABILITY IN LAND AND MARINE SYSTEMS

Clearly, the loss of biodiversity, climate change, and feeding a growing population are three critical and tightly interlinked challenges. While the magnitude of the problem at hand is well understood, the scientific community is increasingly tasked with identifying solutions to support international policies.[161–164] The Green Shoots examples presented here bring to light a number of important opportunities in avoiding dangerous levels of anthropogenic interference in both the climate and socio-ecological systems. Our visual assessment immediately highlights that we are currently (as indicated by the placement of the "c") on the edge of (or below) "sustainability" across most of these indicators, hence the choices made now will have a significant impact on nature and societies in the future; these choices can tip the balance either positively or negatively. Many options to intervene exist that could result in positive outcomes compared to the present day, and some of these could even already be within reach with relatively little additional effort. For instance, reducing fertilizer input (conjointly with other agrochemicals, for which fertilizer is used here as a surrogate) can lead to rapid improvements in biodiversity and climate change without necessarily being detrimental to food production. Nevertheless, the indicators for which data are available for individual countries (Figures S1–S3) provide a reminder of the large discrepancy that exists between countries regarding their "distance" from more sustainable levels on the Green Shoots' surface. There is no reason to believe that this picture would be different for other indicators analyzed, for which we cannot underpin our literature-based assessment with national statistics. Given that the causes of biodiversity loss, climate change, and food insecurity often lie outside of a country's boundaries, and the existing between-country economic inequality, a globally coordinated effort toward sustainability is expected to be much more substantive than uncoordinated national-level interventions.

Due to the large number and variety of solutions discussed in this paper, it is not possible to make a quantitative comparison across different Green Shoots. Nevertheless, side-by-side they provide qualitative evidence of the potential strength of reducing human impacts when different actions are combined, with multiple co-benefits arising for biodiversity, climate change, or food provisioning. Co-benefits were identified already between both extending and improving effectiveness of the protected areas network, and provisioning and regulating ecosystem services.[18] Likewise, positive synergies are obvious between adjusting diets toward an overall healthy and equitable animal protein intake, reducing food waste, and measures to reduce expansion and/or over-intensification in agriculture and unsustainable fisheries (Figure 2C). Large challenges can be expected, however, in achieving these synergies. SDG 12 (responsible production and consumption), for instance, has been identified as the SDG with the highest degree of trade-offs when pairs of SDGs were compared—in this case, with e.g., SDG 10 (reduced inequalities), SDG 1 (no poverty), SDG 6 (clean water and sanitation), and SDG 3 (good health and well-being).[163] Others have found that substantive efforts related to carbon prices and climate financing and access to nutritious food and clean energy are needed to enhance synergies between SDGs.[164]

As things stand, however, many scenarios used in the climate change or biodiversity literature expect future pressure on land and sea use to increase substantially as demand for food increases to feed a growing population with higher per-capita consumption of calories and animal protein, and large land areas dedicated to reforestation/afforestation or bioenergy to combat global warming.[10,82,126] It may be possible to meet these additional demands for land area, but these are accompanied by a high risk of increasing food prices and regional inequity in food supply.[165,166] Still, ambitious future targets in climate change or biodiversity policies are attainable, conditional on our success in increasing agricultural productivity in an environmentally favorable manner and in achieving a globally more equitable diet, especially for the consumption of animal protein.[165,166] These results support the growing consensus of enhanced integration of CBD and UNFCCC targets and related policies with the SDGs.

Critically, it is not only the intervention *per se*, but the effectiveness of its implementation that is fundamental for success. With very few exceptions, this is seen across all of the Green Shoots. While individual studies have previously highlighted the importance of implementing response options "well" (including e.g., the effectiveness of fertilizer use,[167] the "carbon effectiveness" of land use,[168] or effectiveness of protected areas[18,169]) we demonstrate this here across the biodiversity-food-climate nexus. Consequently, a combination of multiple levers is available toward achieving sustainability objectives. Adjusting the analytical framework that underpins the Green Shoots based on regional information provides the opportunity for individual nations to identify their placement on the colored surface. Countries could then decide whether the largest gains for climate, biodiversity, and people can be obtained both regionally and globally by increasing an intervention's effectiveness or increasing the degree of the intervention itself, or both. This will support the adjustment of existing policies and associated investments.

Given the current international policy dynamics such as the targets under the CBD's post-2020 KMGB framework, measures put in place to achieve climate change mitigation and adaptation under the UNFCCC it seems important for the scientific community to support these processes by evaluating and communicating existing opportunities to act. The Green Shoots intend to complement the risk assessment of the Burning Embers by highlighting the solutions that exist to reduce risks—to the environment and consequently also to people—including the potentially large cumulative and synergistic effect of multiple solutions applied simultaneously.

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AUTHOR CONTRIBUTIONS

A.A., P.L., and Y.-J.S. had the original idea for the Green Shoots visualization, which was subsequently elaborated further by all authors. A.A. wrote the first draft and led the assessment that underpins Figures 3A and 3B; P.A. led Figure 2D, R.F. Figures 2A and 2B, and Y.-J.S. Figure 2B. All authors contributed to the writing of the paper and finalizing the figures.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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