An attainable global vision for conservation and human well-being

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A hopeful vision of the future is a world in which both people and nature thrive, but there is little evidence to support the feasibility of such a vision. We used a global, spatially explicit, systems modeling approach to explore the possibility of meeting the demands of increased populations and economic growth in 2050 while simultaneously advancing multiple conservation goals. Our results demonstrate that if, instead of "business as usual" practices, the world changes how and where food and energy are produced, this could help to meet projected increases in food (54%) and energy (56%) demand while achieving habitat protection (>50% of natural habitat remains unconverted in most biomes globally; 17% area of each ecoregion protected in each country), reducing atmospheric greenhouse-gas emissions consistent with the Paris Climate Agreement (≤1.6°C warming by 2100), ending overfishing, and reducing water stress and particulate air pollution. Achieving this hopeful vision for people and nature is attainable with existing technology and consumption patterns. However, success will require major shifts in production methods and an ability to overcome substantial economic, social, and political challenges.

Front Ecol Environ 2018; 16(10): 563–570, doi:10.1002/fee.1965

Analyses of global challenges to biodiversity frequently pit other species' requirements against those of humans (eg Maxwell *et al.* 2016). Conservation prioritizations often address biodiversity targets without fully considering whether solutions leave room to meet people's needs (eg Jenkins *et al.* 2013). On the other hand, analyses of economic development generally prioritize human advancement through continued economic growth while ignoring impacts on biodiversity (eg OECD 2012a).

Several prominent conservation organizations have recently updated their vision statements to include better global conditions for both people and nature. For example, The Nature Conservancy's vision statement now reads: "a world where nature and people thrive, and people act to conserve nature for its own sake and its ability to fulfill and enrich our lives" (TNC 2015). This vision moves beyond the two contrasting views above and is aligned with the Sustainable Development Goals (SDGs) recently endorsed by world leaders.

But can this hopeful vision be attained? We explored the scientific literature for evidence of the feasibility of this positive view and the conservation community's ability to contribute meaningfully to it by 2050. Existing literature has often focused on specific sectors. For instance, analyses of agriculture typically focus on ways to meet growing food demand without expanding agricultural land (eg Foley *et al.* 2011; Tilman *et al.* 2011; Erb *et al.* 2016). Energy analyses explore pathways to meet increasing demand alongside climate goals (eg Rogelj *et al.* 2015; Rockström *et al.* 2017). Conservation analyses define what is needed to protect biodiversity but with limited consideration of human needs (eg Dinerstein *et al.* 2017). These studies provide pathways toward a more positive vision of the future for a particular sector, but they typically fail to address many relevant facets for other sectors, and the potential trade-offs or conflicts among sectors. A few relevant, integrated assessments have been published, but these have been geographically limited (Hatfield-Dodds *et al.* 2015), used less stringent biodiversity targets (van Vuuren *et al.* 2015), or analyzed pathways that either involve dramatic transformations in consumption/technology or fail to achieve the desired positive outcome (see Riahi *et al.* [2017] for an overview of shared socioeconomic pathways).

Here, we used a scenario approach to explore whether achieving multiple desired objectives for people and nature can be attained without heavy reliance on major technological breakthroughs or shifts in consumption patterns (eg reduction

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Figure 1. The Sustainability scenario aims to show how environmental conditions and human well-being can be improved through expansion of several leading conservation strategies, such as (a) transitioning from fossil fuels to renewable energy sources, and siting new renewable energy infrastructure on already converted lands; (b) protecting native habitat at levels that meet national commitments to the Convention on Biological Diversity; (c) shifting agricultural crops within growing regions to where they grow best; and (d) sustainably harvesting all fisheries.

of meat-based protein in diets). We used a global, spatially explicit, systems modeling approach to compare the consequences in 2050 of a "business as usual" scenario (hereafter, "BAU") and a sustainability scenario (hereafter, "Sustainability") that shift production patterns to achieve a set of conservation and economic development goals. The scenario termed Sustainability explored how outcomes change with the expansion of several common conservation strategies such as transitioning from fossil fuels to renewable energy sources, siting new renewable energy infrastructure on converted lands, protecting native habitat, shifting agricultural crops within growing regions, and sustainably harvesting fisheries (Figure 1). The question we addressed is whether it is possible to achieve ambitious conservation and climate goals, along with improvements in fresh water availability and air quality, given current expectations of human population and economic growth.

Methods

For both BAU and Sustainability, we used projected population and gross domestic product (GDP) growth to estimate growth in food, energy, and water demand between 2010 and 2050 (Figure 2; WebPanel 1; WebFigure 1). We relied on the UN midrange values for country-level population growth to estimate a total global population of 9.7 billion people in 2050 (UN 2015), and the US Energy Information Administration's regional estimate of GDP growth between 2010 and 2050 (US EIA 2013). Use of this GDP projection (which was slightly higher [314%] than OECD estimates of global growth; OECD 2012b) allows consistency with energy demand calculations. We used past observed relationships between population, per-capita GDP, and food consumption to model growth in demand for food (54% increase in total crop calorie demand between 2010 and 2050). Our crop calorie demand values more or less matched other recent estimates (eg Alexandratos and Bruinsma 2012; van Vuuren *et al.* 2015). Using a similar approach, we projected increases in energy demand (56% rise between 2010 and 2050) and domestic water demand (234% growth between 2010 and 2050). Changes in agricultural and industrial water demand under BAU and Sustainability are dependent on crop irrigation demand and the energy supply mix.

We then estimated how the production changes necessary to meet these demands would affect land use, water use, air quality, climate, and fisheries. In BAU, we assumed a scale-up of current production methods to meet growing demands. In Sustainability, we altered where and how production occurs to (1) achieve no net loss of natural habitat (defined as unconverted or restored habitat), (2) meet the UN Convention on Biological Diversity's (CBD's) Aichi Targets of 17% protected area, (3) achieve sustainable fisheries, and (4) reduce future greenhouse-gas (GHG) emissions to levels consistent with keeping warming ≤1.6°C above pre-industrial temperatures by 2100. We also tracked progress in reducing water stress and improving air quality. Many model components were taken or modified from previously published models and used in combination to generate a more comprehensive global systems view (see WebPanel 1). Overall, our modeling approach allowed us to address components of 10 SDGs (WebTable 1).

Results

Energy, climate change, and air quality

Under BAU, fossil fuels account for 76% of total energy production in 2050 as compared to 84% in 2010 (Figure 2; WebTable 2; US EIA 2013). Although BAU incorporates some shifts from coal to natural gas and non-fossil-fuel use, CO_2 emissions continue to increase. The resulting BAU emissions trajectory lies between the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway (RCP) 6.0 and RCP 8.5, with an estimated global mean temperature increase of 3.2°C above pre-industrial temperatures by 2100 (Figure 2; WebTable 2).

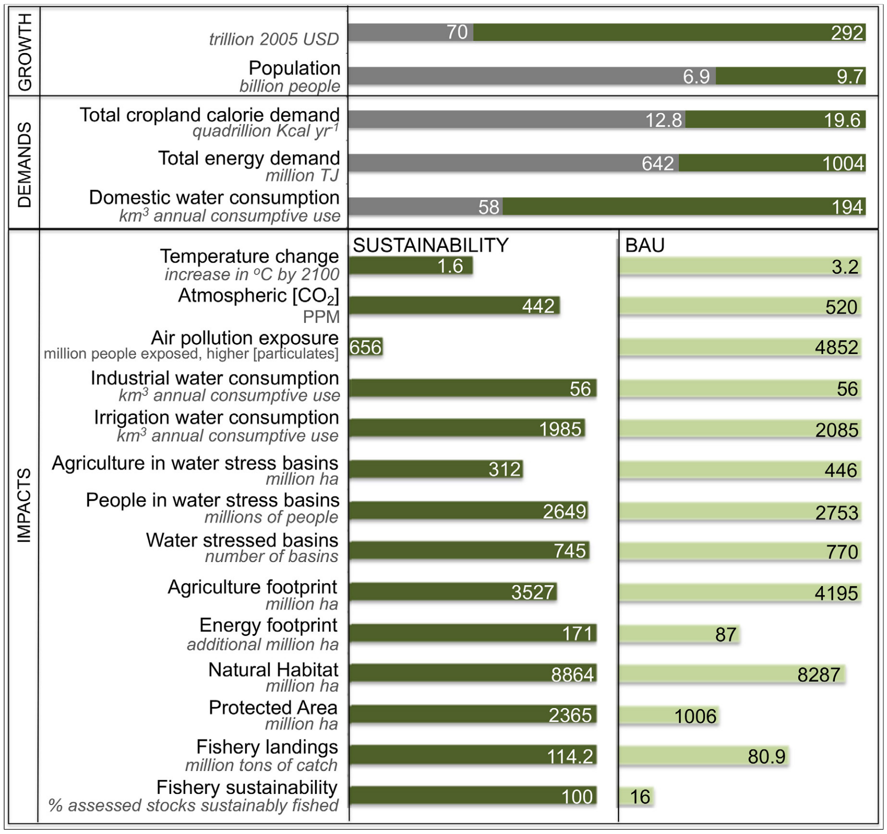

Figure 2. Summary of 2050 BAU and Sustainability scenarios. We assumed the same growth in population and GDP in both scenarios, expanding from 2010 (gray bars) to 2050 (green bars). Population and GDP growth were then used to predict growth in demand for food, energy, and water from 2010 (gray bars) to 2050 (green bars). Impacts on climate, air pollution, land, water, and fisheries varied between Sustainability (dark green bars) and BAU (light green bars) scenarios. Water stress for population and agricultural area was defined as basins where >40% of precipitation within the basin is consumed by human uses each year. Water stress for biodiversity was defined as basins where >20% of precipitation is consumed by human uses each year. Natural habitat reflected all land not under agricultural, energy, or urban development. Protected areas (a subset of natural areas) represented all lands in International Union for Conservation of Nature Classifications I–IV. Sustainable fisheries were assumed to be fished at maximum sustainable yields. All variables are shown scaled to the maximum value. USD = US dollars; Kcal = kilocalories; TJ = terajoules; PPM = parts per million.

Under Sustainability, CO_2 emissions are constrained to follow IPCC RCP 2.6, limiting the global mean temperature increase to 1.6°C above pre-industrial temperatures by 2100. Fossil-fuel production falls to 13% of total energy production by 2050, with 54% of energy supply coming from renewable sources (wind, solar, geothermal, biomass, hydro; biofuels are excluded in this scenario) and 33% from nuclear energy (Figure 2; WebTable 2). Investment in carbon capture and storage technology would allow a fossil-fuel proportion higher than the 13% reported here. Given concerns about nuclear accidents, waste, and proliferation, we also investigated a case without nuclear energy, in which climate and natural habitat protection goals were met but resulted in a larger energy land footprint, leaving less natural habitat outside of protected areas (WebPanel 1). A large-scale shift to renewables, such as that required in Sustainability, is technologically feasible (Jacobson *et al.* 2015) but will require overcoming problems with variable energy supply through better storage, smart grids, and demand management (Clack *et al.* 2017; Heard *et al.* 2017).

Regional air quality is tightly linked with energy production and industrial activity. Emissions of air pollutants (such as particulate matter and associated precursors) are a major cause of premature mortality (Landrigan *et al.* 2017). In both scenarios, improvements in air quality occur in many middle- and upper-income countries by 2050 due to expected increases in the use of emissions control technology as incomes rise. However, in BAU, exposure to particulate air pollution in multiple African nations, Brazil, and India worsens because of increased fossil-fuel use and population growth, exposing regions with 4.9 billion people in 2050 to poorer air quality than in 2010 (Figure 2; WebTable 2). In contrast, Sustainability's dramatic shift in energy sources away from fossil fuels leads to a massive reduction in air pollution exposure, with only 0.7 billion people expected to live in areas with lower air quality in 2050 (Figure 2; WebTable 2); this scenario does not make any assumptions about changes in air quality policies, which could aid in even greater reductions in air pollution by 2050.

Land use for food, energy, cities, and conservation

We accounted for the location and total land area in food production, energy production, urban development, and natural habitat. In both scenarios, current protected areas (International Union for Conservation of Nature [IUCN] Categories I–IV) are not permitted to transition from natural habitat. Protected areas are expanded further under Sustainability, assuming that all countries meet targets established by the CBD (17% of each ecoregion within each country protected; Figure 2; WebTable 2).

In both BAU and Sustainability, per area crop yields are projected to increase ("intensification"). We projected increased yields in 2050 based on empirical relationships between yields and growth in per capita GDP for regions defined by geography and climate (WebPanel 1; WebFigure 1). Most of the increased demand for crops in both scenarios is met through intensification rather than "extensification" (ie expansion of cropland). In BAU, net cropland expands by 27 million ha, which is a somewhat smaller increase in the agricultural footprint than that estimated by the UN Food and Agriculture Organization (Alexandratos and Bruinsma 2012; WebTable 2). We assumed total pastureland area will remain stable between 2010 and 2050; however, some pasture will be displaced by cropland, requiring conversion of some unprotected natural habitat to pasture. In Sustainability, we increased crop production in higher productivity areas, thereby allowing increased calorie demand to be met on less land area (Figure 3); under this scenario, cropland declines by over 200 million ha and pasture declines by over 400 million ha by 2050 relative to 2010 (Figure 2; WebTable 2). Required calories could be produced in an even smaller area by more fully optimizing crop placement. However, we restricted crop relocation in Sustainability to avoid assumptions of major trade and/or transport changes that would be needed if substantial relocation were allowed. We accomplished this by maintaining the set of crop types present today within each major global growing region and requiring at least 75% of 2010 cropland to remain under production in each country in 2050.

Given the uncertainty in projections of agricultural response to climate change, we assumed no net effect of climate change on agricultural yields under either scenario. The net effect of climate change on agriculture depends on responses to temperature, precipitation, CO_2 fertilization, and management adaptation, and modeled projections of impacts remain uncertain (Nelson *et al.* 2014; Huang and Sim 2018). By keeping warming in 2100 below 1.6°C and shifting agriculture to areas with less water stress, Sustainability would avoid many climate impacts, which are expected to primarily occur after 2050, even under BAU (Urban *et al.* 2015). If climate impacts have a net negative impact on agriculture, this would further the difference between BAU and Sustainability, making our results here conservative.

The land required for extracting, producing, and transporting energy is larger in Sustainability than in BAU (171 million ha versus 87 million ha of additional area in 2050, respectively; Figure 2) because of the larger per unit area requirements for wind and solar energy (WebTable 3). However, there is more flexibility in siting renewable energy than in siting fossil fuels, allowing renewable energy expansion to occur on already converted agricultural land. Eliminating nuclear energy in Sustainability succeeds in meeting the climate target and multiple other targets but has a larger land impact, requiring an additional 245 million ha for energy production in 2050.

Projected urban area expansion is 187 million ha (1.4% of total land area) in both scenarios (Figure 2; WebTable 2). This estimate is derived using UN projections for changes in urban population along with estimates of regional urban population density (WebPanel 1). We did not account for differences in consumption between rural and urban areas beyond those anticipated due to changing incomes, nor did we account for other environmental impacts or benefits of urbanization (Gill and Moeller 2018).

Overall, Sustainability results in no additional conversion of natural habitat for combined food, energy, and urban growth needs, and retains 577 million ha more natural habitat than BAU (Figure 3). Under Sustainability, over 50% of each of 14 global biomes remains as natural habitat, with the exception of temperate grasslands (a biome that has already lost nearly 50% of its former extent as of 2005; Hoekstra *et al.* 2005) (WebFigure 3; WebTable 4). Sustainability is therefore largely compatible with emerging views on the need to protect half of the Earth's land system (Dinerstein *et al.* 2017). In contrast, temperate broadleaf and mixed forest, Mediterranean forest, and temperate grassland each lose >50% of their potential global extent by 2050 with BAU (WebFigure 3). Whether Sustainability is sufficient for biodiversity conservation depends on additional factors not modeled here, including edge effects, fragmentation, endemicity, habitat degradation, and climate-change impacts. More robust analyses that incorporate more of these effects are needed to increase confidence that biodiversity will be conserved.

Fresh water

Water extraction threatens freshwater biodiversity, and water shortages represent major challenges for food production, energy generation, public health, and economic development. Both BAU and Sustainability allow for the same projected increases in domestic and industrial water demands (WebTable 2). However, the amount of water used for irrigation, the dominant consumptive water use globally, differs between scenarios, as do the levels of water stress that people and biodiversity experience (Figure 4; WebTable 2). For human needs, we defined water-stressed basins as first-order river basins (Flörke *et al.* 2013) where >40% of available water is consumed by human uses. For biodiversity, we used a more stringent threshold, identifying water-stressed basins as first-order basins where 20% or more of available water is consumed by human uses.

In BAU, irrigation expands proportionally to agricultural production in each watershed, resulting in 2085 km^3 of consumptive water use in 2050 (Figure 2; WebTable 2). Water stress affects 446 million ha of cropland, 2.75 billion people and biodiversity in 770 basins (Figure 2; Figure 4; WebTable 2) in BAU. In Sustainability, irrigation water use is ~5% lower than that in BAU in 2050 (Figure 2). More importantly, water use is redistributed to less water-stressed regions, resulting in 30% less water-stressed crop area, as well as a reduction in the threat of water insecurity for 104 million people and for biodiversity in 25 major water basins (Figure 4). The same redistribution of crops that allowed land area savings, described above, reduces irrigation water demands.

Fisheries

We used an amended approach from Costello *et al.* (2016) to estimate the supply of calories produced by wild fisheries, scaling up their projected yields to account for fisheries excluded from their analysis (WebPanel 1). In BAU, 84% of assessed fisheries are expected to experience overfishing in 2050, lowering annual catch by 11% relative to 2010 (Figure 2; WebTable 2). In Sustainability, managing all fisheries for maximum sustainable yield (MSY) increases harvest to 114 million tons annually, a 26% increase from the 2010 harvest (Figure 2; WebTable 2). In both scenarios, we assume that combined aquaculture and wild-caught fisheries supply 7% of total animal calorie demand, the same percentage as in 2010. This estimate is conservative, given that aquaculture is the fastest growing food-producing sector (WebPanel 1; Gentry *et al.* 2017).

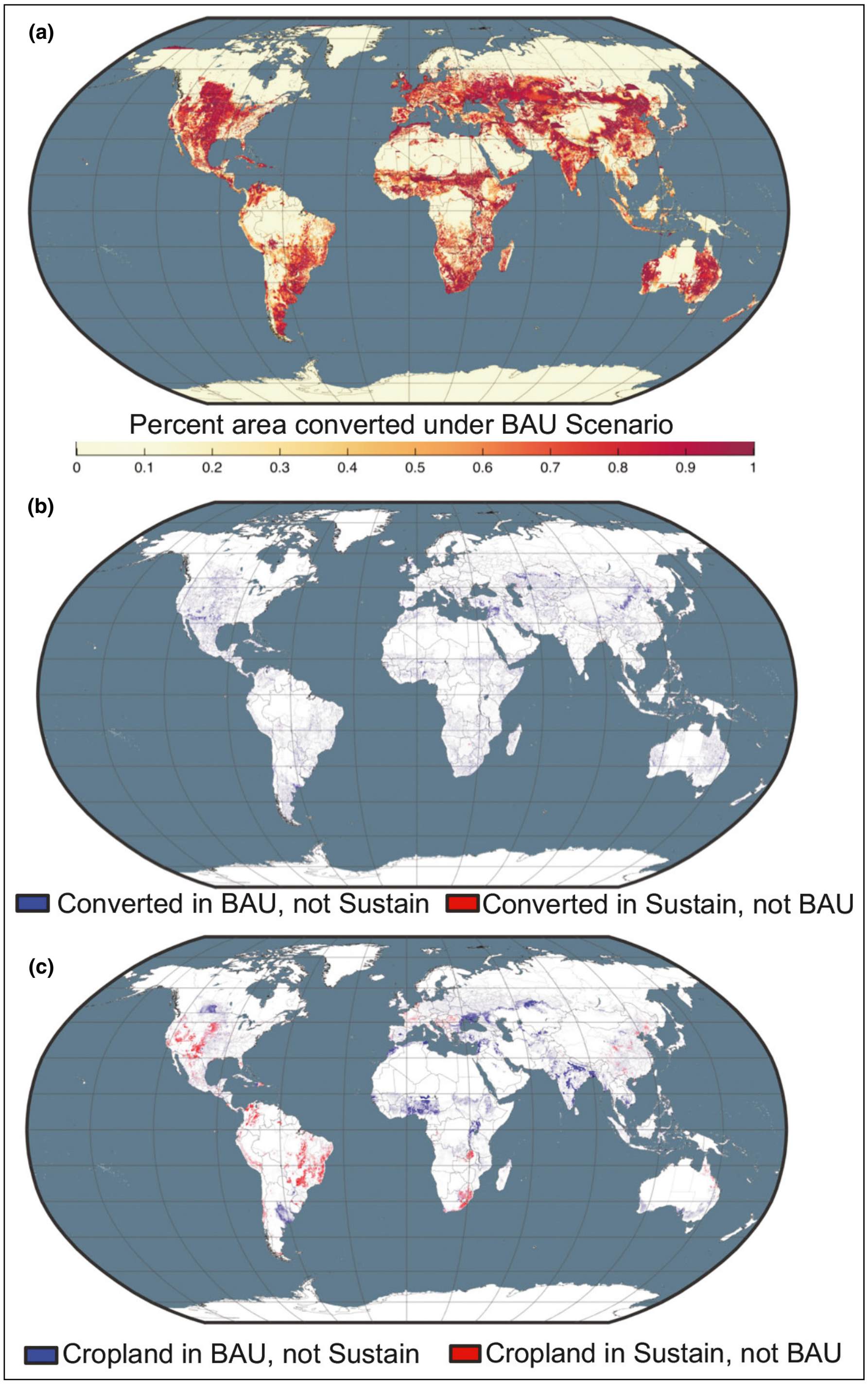

Figure 3. Land conversion patterns and differences in 2050. (a) The global spatial pattern of converted land in 2050 under BAU. (b) Sustainability projects 577 million ha less natural habitat conversion to meet urban growth, and increased food and energy production between 2010 and 2050 compared to BAU. (c) Calorie needs are met on a smaller total area but with redistribution among regions under Sustainability compared to BAU.

Discussion

BAU illustrates what many in the environmental community fear about unfettered economic growth. Simply scaling up current production methods, doing more in the same way in the same places, will exacerbate future environmental problems, including additional loss of natural habitat and biodiversity, intensified climate change, increased air pollution, heightened water stress, and further fisheries collapse. In contrast, Sustainability represents an ambitious set of environmental advances and avoided losses relative to BAU. This alternative meets the same projected 2050 demands for

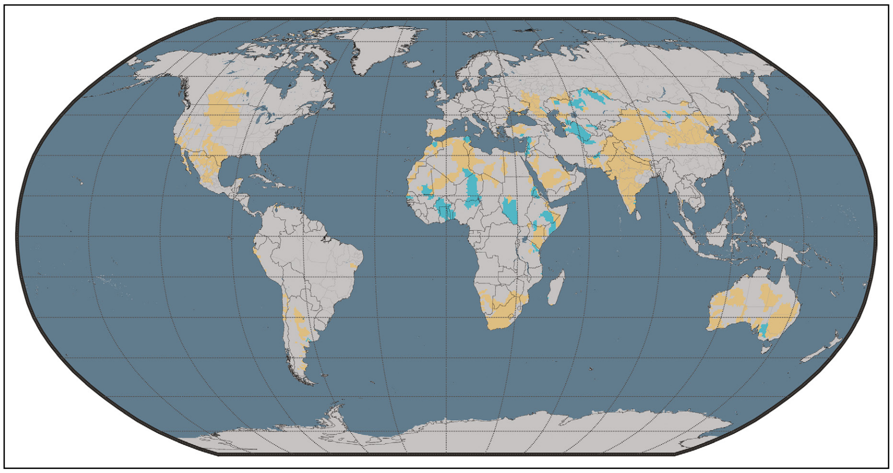

Figure 4. Water basins where agricultural areas and people face water stress (>40% annual precipitation being consumed). Brown watersheds are water stressed under both BAU and Sustainability, whereas blue watersheds are water stressed only under BAU and not under Sustainability.

food, water, energy, and other goods and services as BAU, but does so with no net loss in natural habitat from 2010 levels, greater than 50% of natural habitat remaining in all biomes except temperate grasslands, limited global warming to less than 1.6°C above pre-industrial levels by 2100, reduced air pollution and water stress, and maintained high-yielding sustainable fisheries. These outcomes do not ensure conservation of all species and ecosystem services (Rey Benayas *et al.* 2009; Moreno-Mateos *et al.* 2017) but do represent an ambitious set of advances for the environment. The subset of environmental and economic objectives analyzed here can be achieved by adjusting how and where economic activity occurs: shifting agricultural production to areas with higher yields and lower water stress, transforming energy production from primarily fossil fuels to renewable and nuclear energy, siting new energy infrastructure on already converted land, and sustainably managing fisheries.

Our analyses suggest that the biophysical limits of a finite planet by themselves may not constrain more sustainable development. Rather, it is the complex interactions between social, economic, political, and biophysical systems that make sustainable development such a daunting challenge. Moving from BAU to something more closely resembling Sustainability will require overcoming major economic, political, and social challenges. Current market mechanisms tend to promote actions that are profitable for a relatively small group of people in the short term rather than sustainable actions that are beneficial globally over the long term. Despite the growing recognition of the importance of conserving ecosystems and biodiversity, responses in business and government systems have been limited (Guerry *et al.* 2015). Reformed policies and institutions are needed to align private short-term goals with societal short- and long-term objectives. Although it is possible to modify incentives, as in land conservation programs (Ouyang *et al.* 2016) and catch–share fisheries (Costello *et al.* 2008), failure to address climate change, biodiversity loss, and a host of other global environmental problems highlights just how difficult it can be to reform institutions and policies to create incentives for sustainability (Oreskes and Conway 2010).

Our analyses did not take into account several other elements that may alter findings or that may make achieving sustainable development more difficult. We assumed the same population and economic growth in both scenarios, which allowed us to quantify the effects of changes in where and how food and energy is produced but did not explore different economic or population growth assumptions or their impacts. We also did not consider the environmental, economic, or social impacts of different rates and patterns of urbanization. Likewise, our scenarios accepted BAU expectations in regional economic performance, so benefits or challenges of variations in these patterns were not explored. Further exploration of these topics would identify additional opportunities to meet goals for nature and people.

In addition, we were not able to explore the full set of SDGs, including the potential to alleviate all poverty and reduce economic inequality. Projections of economic growth (US EIA 2013) show large regional differences, with remaining pockets of low income – particularly in sub-Saharan Africa – continuing into the future. Bringing sub-Saharan Africa and other low-income regions up to standards similar to those present in the developed world today would require a major redistribution of wealth across countries or greater overall economic growth than currently projected. Furthermore, the potential for trade-offs between reductions in GHG emissions and aerosols was not included, and such trade-offs may make meeting climate targets more challenging (Smith *et al.* 2016). Most models and projections we applied did not include mechanisms related to crossing Earth-system tipping points that may have large negative impacts on sustainable development (Rockström *et al.* 2009). Part of the argument for a transition away from BAU to Sustainability is to reduce the likelihood of crossing such tipping points.

By illustrating at least one potential pathway that achieves many elements of sustainable development, we hope to spur the global community to engage more aggressively in the difficult but necessary social, economic, and political dialogue that will make a sustainable future more likely. The scenario termed Sustainability is one of many possible versions of a future with more balanced gains for the environment, people, and the economy. Our results demonstrate that existing technologies and large-scale adoption of common conservation approaches (eg protected area establishment, energy siting, fisheries management, agricultural best management practices) can make a meaningful contribution to the advance of multiple economic and environmental objectives.

Acknowledgements

We thank The Nature Conservancy, as well as the Institute on the Environment and the Fesler-Lampert Endowment at the University of Minnesota, for support.

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Supporting Information

Additional, web-only material may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/fee.1965/suppinfo

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FrontiersEcoPics

A rattlesnake finds refuge

In early September 2017, Hurricane Irma made landfall in southwest Florida, bringing with it strong winds and heavy flooding. At that time, a radio-telemetry project was being conducted on eastern diamondback rattlesnakes (*Crotalus adamanteus*) at the campus of Florida Gulf Coast University in Fort Myers, Florida. After the storm, this large radio-tagged female was found perched about two meters off the ground, atop a fallen cypress tree and other debris, surrounded by flood waters.

Eastern diamondback rattlesnakes are typically sedentary predators that maintain relatively small home ranges (approximately 30–60 hectares) and will remain stationary for several days at a time. However, individuals in this study traveled long distances in the days to weeks after Irma made landfall. This may have been due to storm surge inundation limiting available space to rest, thermoregulate, and protect themselves. These snakes are also typically solitary; however, we encountered multiple rattlesnakes congregating on the small islands created by the hurricane.

These observations provoke many behavioral and life-history questions for this species. Eastern diamondback rattlesnakes have often been documented crossing saline waters and barrier islands but where do they seek refuge during flooding events? Do survival rates differ across age classes? These disturbances can also cause drastic alterations to landscapes, so do hurricanes have long-lasting effects on how these snakes use their habitats? Like the populations of many other native snakes in the southeastern US, *C adamanteus* populations are in decline throughout their range. Particularly for Eastern diamondback rattlesnakes residing near coastal areas, how this species responds to hurricane events may be a vital aspect of their life history that is overlooked during management decisions.

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doi:10.1002/fee.1981