ECOSYSTEM SERVICES

# Global modeling of nature's contributions to people

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**The magnitude and pace of global change demand rapid assessment of nature and its contributions to people. We present a fine-scale global modeling of current status and future scenarios for several contributions: water quality regulation, coastal risk reduction, and crop pollination. We find that where people's needs for nature are now greatest, nature's ability to meet those needs is declining. Up to 5 billion people face higher water pollution and insufficient pollination for nutrition under future scenarios of land use and climate change, particularly in Africa and South Asia. Hundreds of millions of people face heightened coastal risk across Africa, Eurasia, and the Americas. Continued loss of nature poses severe threats, yet these can be reduced 3- to 10-fold under a sustainable development scenario.**

Evidence on how human actions cause environmental change, and how environmental change affects human well-being, can provide the basis for sound investments in nature benefitting people (*1*). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) was established to synthesize and advance science supporting such investments (*2*, *3*) and recently completed its first Global Assessment compiling the overall status and trends of nature's contributions to people (*4*). However, spatially explicit modeling of many of these contributions, showing where nature matters most to people over global extents, has remained a major challenge (*5*).

Thanks to rapid improvements in spatial data, computation, and visualization, nature's contributions to people can now be quantified at policy-relevant scales in an accessible, integrated, and globally consistent way. Here, we model three vital contributions spanning three realms of the biosphere (freshwater, coastal, and terrestrial) and representing contrasting biophysical processes: regulation of drinking-water quality through nitrogen retention, coastal risk reduction of hazards such as shoreline erosion and flooding, and wild pollination of crops for human nutrition.

The spatial dependence of the socioecological processes governing these contributions of nature to people require fine-scale data, differentiating them from the coarser-scale global mapping of contributions such as carbon sequestration and storage (*6*). For example, a wetland downslope from a farm absorbs excess fertilizer; mangroves, coral reef, and coastal marshes close to vulnerable human communities confer storm protection; and a bee habitat within flight distance of crops enables wild pollination. To perform such fine-scale analysis over continental or global extents requires advanced computational capabilities. Previous global modeling approaches have disregarded spatial configuration of nature, in the case of coastal risk reduction (*7*), or have not accounted for the role of nature at all in retaining pollution (*8*, *9*) or providing pollinators to farmland (*10*, *11*) and thus cannot project how degradation of nature can affect human well-being. Our approach uses spatially explicit modeling to operationalize the IPBES conceptual framework for nature's contributions to people (*12*), which is achieved by enhancing and scaling up the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) modeling platform with free and open-source data and software (*13*) that have been widely deployed at regional to national scales (*14*).

We consider the dual dimensions of nature's contributions to people—(i) people's needs and (ii) nature's contributions (Fig. 1 and fig. S1)—and distinguish these contributions from ecosystem services (corresponding to "realized benefits" in Fig. 1) by considering the proportion of potential benefit provided by nature. A proportional representation is important to track differences or changes across space and

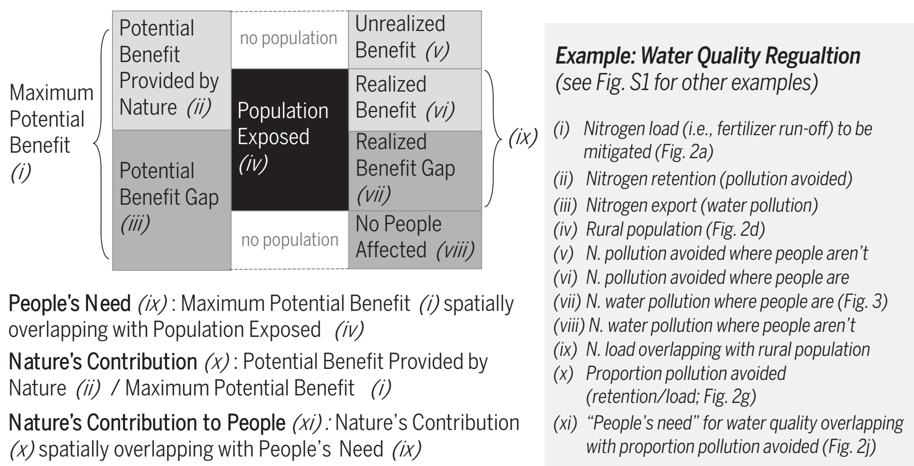


**Fig. 1. Conceptual framework for calculating nature's contributions to people, with terms corresponding to Figs. 2 and 3.** Maximum potential benefit (i) is based on conditions that create a human need for a benefit (see example at right, numbered corresponding to the figure). Some of this maximum potential benefit can be provided by nature (ii), and some likely cannot, leading to a potential benefit gap (iii). The maximum potential benefit, together with the population exposed (iv) to the benefit or threat, combine to form people's need (ix). In this framework, we do not consider the unrealized benefit (v) that people do not need or where no people are affected by lack of benefit (viii). The realized benefit gap (vii) is the part of people's need that is not met by nature and is often the most visible impact to people. The realized benefit (vi) is commonly considered the "ecosystem service," which may increase simply because of greater need even without any change in nature. Thus, we consider the proportion of the maximum potential benefit provided by nature to be nature's contribution (x). Together, nature's contribution and people's need determine nature's contribution to people (xi).

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time because realized benefits provided by nature could increase alongside or because of increases in maximum potential benefits (e.g., increased fertilizer runoff requiring mitigation) or population exposed (e.g., greater number of rural people affected by water contamination), although nature's contributions may remain the same. The relative proportion of nature's contribution along with people's needs, especially for the most vulnerable people, is a more useful metric than realized benefits alone when considering change across several variables at once (stressors, people, and nature) because they reveal where and when nature plays a key role in delivering benefits.

We also examine the benefits not provided by nature, or benefit gaps, and the people whose well-being may be compromised by inadequate water quality regulation, coastal risk reduction, or pollination. These benefit gaps are the outcomes people will actually face and perceive unless they are filled by other forms of capital, such as water treatment plants, sea walls, or hand pollination. Benefit gaps are what determine people's well-being, the tangible component of nature's contributions to people, but they do not by themselves reveal the role nature plays in contributing to that well-being.

Applying this framework to operationalize nature's contributions to people, we ask two key questions. First, where is nature currently contributing most to people? And second, how many people may be affected—and where—by future changes? We examine changes from current (2015) conditions to the future (2050) under scenarios of land-use, climate, and population change according to the Shared Socioeconomic Pathways (SSP) (*15*). The pathways are not forecasts of the future but describe plausible major global developments (*16*, *17*). We use three contrasting SSP narratives following the IPBES Global Assessment (*4*): a minimal-human-footprint vision of "sustainability" with high-intensity agriculture and urbanization, an agriculturally expansive future in "regional rivalry" due to minimal trade and high population growth, and "fossil-fueled development" with unmitigated climate change (table S1).

To address the first question, we quantify and map the overlap between people's needs and nature's contributions (Fig. 2). We first identify places with the greatest potential for benefit: the highest pollution loads requiring retention, highest potential coastal hazards requiring mitigation, or highest crop production requiring pollination. These places are unevenly distributed for all contributions examined (Fig. 2, top row) and not always overlapping with the populations that are most reliant on those benefits (Fig. 2, second row). People's needs are greatest where the highest potential benefits overlap with the highest populations exposed. The proportion of potential benefits provided by nature ("nature's contributions"; Fig. 2, third row), regardless of whether people realize the benefits, is predictably highest where nature is most intact.

However, protection of nature will provide the greatest benefits to people where people's greatest needs coincide with nature's highest contributions (Fig. 2, bottom row, regions in black). Areas where people's needs are high and nature's contributions are low indicate benefit gaps (Fig. 2, bottom row, dark pink), manifested as pollutants not retained by



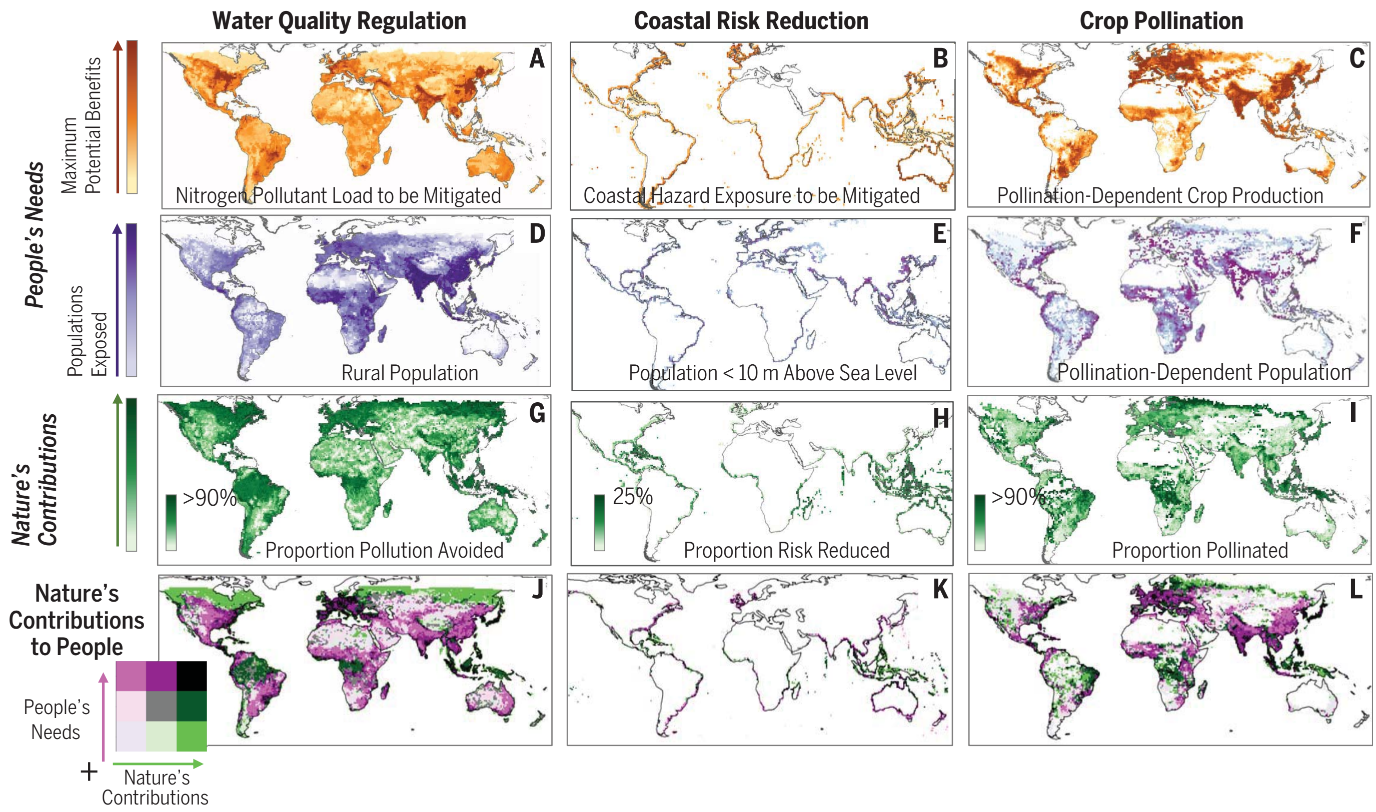


**Fig. 2. Global variability in nature's contributions to people, for water quality regulation, coastal risk reduction, and crop pollination.** These are quantified in terms of (**A** to **C**) (row 1) maximum potential benefits; (**D** to **F**) (row 2) population exposed to benefits or threats (rural population with presumed lower access to water treatment, coastal population falling within 0 to 10 m above mean sea level, and population whose nutritional requirements are not solely met by pollination-independent crop production within 100 km); (**G** to **I**) (row 3) nature's contribution to providing potential benefits (proportion of pollution avoided because nitrogen was retained by vegetation, proportion of coastal risk reduced by coastal habitat, and proportion of crop pollination needs met); and (**J** to **L**) (row 4) nature's contribution to people, depicted as combined ranks of humanity's need (derived from combined ranks of pixels in maps from rows 1 and 2, in pink) and nature's contribution (ranked from row 3 in green), with black indicating the highest overlap.

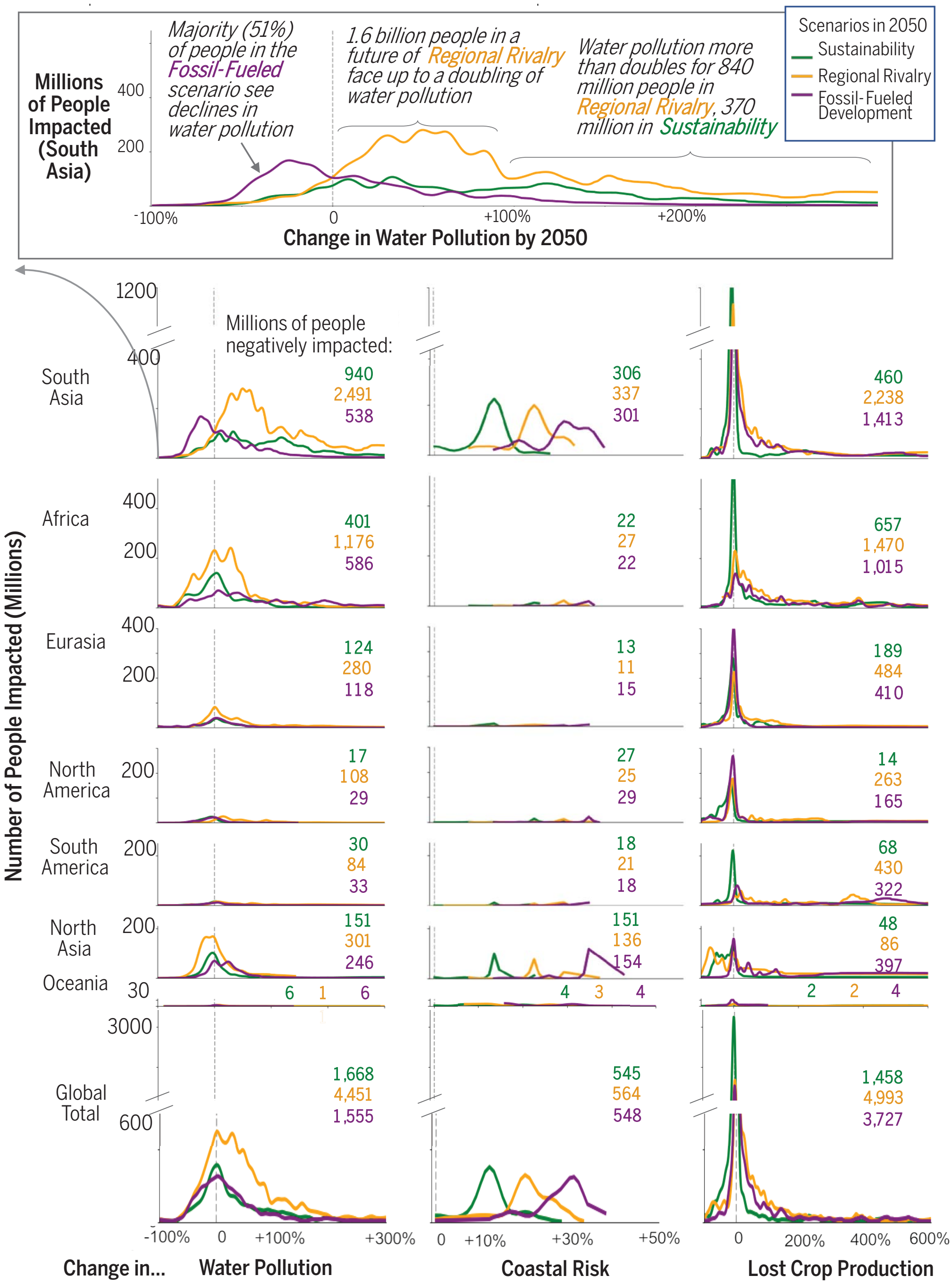


**Fig. 3. Future conditions result in highly uneven changes in benefit gaps (Fig. 1) across regions and scenarios.** (Inset at top) A schematic of how to interpret the results, using South Asia as an example. Plots show the number of people affected (population exposed from Fig. 1) by different magnitudes of change in benefit gaps (nitrogen pollution in drinking water, risk of coastal hazards, and lost crop production due to insufficient pollination) for future scenarios of sustainability (SSP 1, RCP 2.6) in green, regional rivalry (SSP 3, RCP 6.0) in yellow, and fossil-fueled development (SSP 5, RCP 8.5) in purple. Numbers inset in each plot show millions of people negatively affected in each scenario (colored accordingly). RCP, representative concentration pathway.

vegetation before entering waterways, coastal hazards unmitigated by habitats, and crop losses from insufficient wild pollination. These mark potential opportunities for ecosystem restoration to boost nature's contributions to people, perhaps together with other investments necessary to ensure and sustain well-being.

To address the second question of where and how many people may be affected in the future, we examine the change in benefit gaps faced by different populations. Globally, up to 4.5 billion people face higher water pollution, and 5 billion may experience local losses in crop production due to insufficient pollination, although the number of people affected in different regions could be diminished 3- to 10-fold under a sustainability trajectory (Fig. 3). Future impacts are inequitably distributed across all scenarios, with hundreds of millions of people across the globe facing benefit gaps that more than double, whereas some gaps (water pollution and crop losses) shrink for a majority of people in North Asia and North America in multiple scenarios (Fig. 3). By contrast, regardless of scenario, coastal risk increases everywhere with projected sea-level rise under climate change, affecting more than half a billion people globally by 2050. A small proportion of the population in every region is exposed to large increases in benefit gaps, as indicated by long tails on the distributions.

Developing countries bear a disproportionate share of the impacts across scenarios. Africa and South Asia are the most disadvantaged across all scenarios for all three contributions of nature to people, with well over half the population across both regions facing higher-than-average benefit gaps, accounting for up to 2.3 billion people exposed to greater increases in water pollution, 1.7 billion facing greater additional crop losses due to insufficient pollination, and nearly 300 million facing greater increases in coastal risk than the rest of the world (table S2). The average impacts are two to six times higher in Africa than in other regions across all scenarios and up to 10 times higher in South Asia in the sustainability scenario. Indeed, twice as many people in South Asia experience higher water pollution in this supposed sustainable future than under fossil-fueled development, likely because of the agricultural intensification in the former that results in much higher nitrogen fertilizer applications (fig. S3). However, people in this fossil-fueled future fare far worse in Africa, where the largest proportion of people globally face above-average increases in benefit gaps (table S3).

Although the models differ in their major sources of uncertainty (e.g., nitrogen loads driving variability in water quality; coastal habitat response to urbanization for coastal risk reduction; assumptions about the importance of local food supply, insensitivity to climate, and habitat quality for pollination) and lack of calibration precludes interpretation of absolute values of model outputs, relative differences between regions and scenarios as explored here have been shown in previous study to be fairly robust (*12*). Further work is needed to move beyond spatial overlays with population and better represent dimensions of social vulnerability and human dependence on nature, especially in terms of the availability of substitutes for natural capital (e.g., through built, technological, social, and human capital or teleconnections and trade). Yet this approach to quantifying nature's contributions to people can be made more rigorous as our data and science continue to improve.

Considering both nature's contributions and people's needs illuminates policy options. This fine-scale mapping suggests that there are relatively consolidated areas that could be targeted to close benefit gaps (e.g., in the Ganges Basin and eastern China in South Asia and in much smaller pockets across sub-Saharan Africa; fig. S2), and examination of the natural and human dimensions of nature's contributions to people helps identify where interventions could enhance the role nature plays and where solutions should be focused on reducing people's needs. Science can provide key information for policy by connecting indicators that are measured and managed (e.g., water pollution, coastal hazards, crop losses—the benefit gaps) with the less visible yet vital roles that nature plays in filling such gaps.

The approach illustrated here is but one dimension of a much broader, systemic change needed—both in societal awareness of the importance of nature's contributions to people and in their integration into decision-making—highlighting where investments in nature may confer the greatest benefit to people, especially those who are most in need. There are a growing number of opportunities around the world for science to inform such investments, at local to national scales (*1*, *18*–*20*). Ultimately, revealing nature's contributions to people, in diverse and accessible terms, is an essential step to averting the worst scenarios and transforming to a world in which both people and nature thrive.

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## SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/366/6462/255/suppl/DC1
Materials and Methods
Figs. S1 to S3
Tables S1 to S3
References (*22*–*77*)

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**The future of nature's contributions**

A recent Global Assessment by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services has emphasized the urgent need to determine where and how nature's contribution matters most to people. Chaplin-Kramer *et al.* have developed a globalscale modeling of ecosystem services, focusing on water quality regulation, coastal protection, and crop pollination (see the Perspective by Balvanera). By 2050, up to 5 billion people may be at risk from diminishing ecosystem services, particularly in Africa and South Asia.

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