NATURE UNBOUND

DECOUPLING FOR CONSERVATION

BY LINUS BLOMQVIST, TED NORDHAUS, AND MICHAEL SHELLENBERGER

BREAKTHROUGH INSTITUTE

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ABOUT THE AUTHORS

Linus Blomqvist is Director of Conservation at the Breakthrough Institute.

Ted Nordhaus and Michael Shellenberger are cofounders of the Breakthrough Institute, where they are Chairman and President, respectively.

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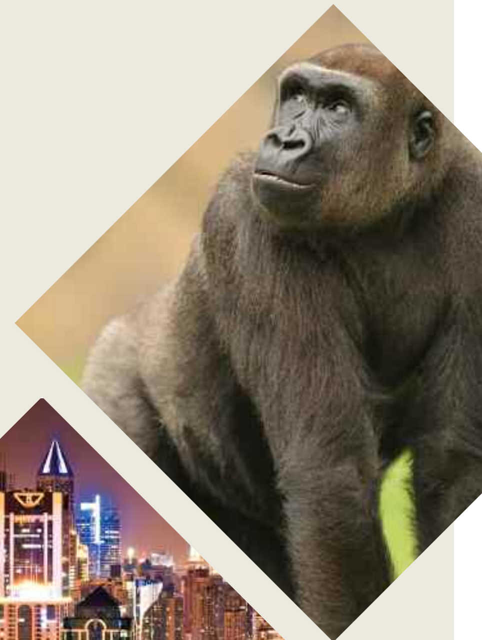
EXECUTIVE SUMMARY



HUMAN SUCCESS HAS COME AT THE EXPENSE OF NONHUMAN LIFE. Since 1900, the human population has more than quadrupled and per-capita income has increased at least fivefold. Global average life expectancy at birth has more than doubled in this time span, and the number of people living in extreme poverty has declined. At the same time, demand for food, water, energy, materials, and living space has increased manifold. The production of these goods and services has entailed widespread biodiversity loss through impacts ranging from wildlife harvesting to land-use change, water extraction, and pollution. Wildlife harvesting includes hunting of wild animals for their meat or for medicinal and ornamental uses, wild fish harvests, and whaling, all of which have severely decimated populations and caused local extinctions. Fuelwood extraction causes widespread forest degradation. Humans today actively use nearly half of earth's ice-free land, displacing and fragmenting natural habitats. Pastures account for 26% of global ice-free land, cropland 12%, production forest 9%, and cities less than 3%. Freshwater extraction impinges on freshwater ecosystems in many of the world's river basins. Pollution causes harm to nonhuman life through toxicity, acidification, eutrophication, and global warming, among other effects.

ALTHOUGH MANY OF HUMANKIND'S ENVIRONMENTAL IMPACTS HAVE GROWN IN ABSOLUTE TERMS, SEVERAL HAVE PLATEAUED OR HAVE STARTED TO DECLINE, AND MOST IMPACTS HAVE DECLINED ON A PER-CAPITA BASIS. Slowing population growth, demand saturation in developed countries, and improved technological efficiencies have all contributed to what is known as decoupling. Relative decoupling refers to impacts growing at a slower rate than population or consumption. Absolute decoupling means impacts are declining in absolute terms. The per-capita farmland requirement (cropland and pasture) has declined by half in the last half-century. In absolute terms, cropland has expanded 13% and pasture 9% in that time period, but the sum of the two has remained stable since the mid-1990s. Global consumption of wood has plateaued, contributing to a slight decline in the area of production forest since 1990. While overharvesting of wild animals for meat has increased in the tropics, most developed countries have decoupled from this form of impact. The world has almost entirely decoupled from whaling. Total water consumption increased by 170% between 1950 and 1995, but per-capita water consumption peaked around 1980 and declined thereafter. The least decoupled environmental impact is greenhouse gas emissions from energy: global per-capita emissions increased by nearly 40% between 1965 and 2013.

HUMANS SPARE NATURE FROM USE THROUGH THE CREATION OF SUBSTITUTES. Going from wildlife harvesting, to the controlled production of biomass in agriculture and forestry, to fully synthetic means of providing material goods has historically lowered the amount of environmental impact per unit of production. Farmed instead of wild meat takes pressure off wild animal populations. Farmed meat requires land, but this impact is less severe, per unit of meat produced, than the harm caused by wildlife hunting. Feedlot systems require far less land than grass-fed systems. The emergence of cheaper and better substitutes for whale oil in illumination explains the decline in whaling in the 19th century. Aquaculture increasingly takes pressure off wild fish stocks as feed-to-meat conversion ratios improve and plant-based feeds substitute fish-based feeds. Forests are spared when humans move from reliance on wood fuel to modern energy. Replacing organic with synthetic fertilizer eliminates the need to allocate land for nitrogen fixation. Substituting synthetic fiber and rubber for their natural counterparts reduces the land required to produce these goods. Tractors substitute draft animals, freeing up land previously dedicated to growing animal feed.

INTENSIFICATION — PRODUCING MORE OF A GOOD ON THE SAME AMOUNT OF LAND — REDUCES THE HUMAN LAND FOOTPRINT. Increasing yields in farming or forestry, as well as denser settlements, are examples of intensification. Agricultural intensification causes biodiversity loss on farmland, but reduces the need to convert natural habitats to farmland. In many regions, especially the tropics, the biodiversity loss from conversion is greater than the loss from intensification, such that intensification benefits biodiversity overall. However, the land-sparing benefits may fall outside the region whose yields have improved. Rising agricultural productivity in tropical regions has contributed to a shift in agricultural production away from temperate regions, facilitating forest regrowth in the latter but driving deforestation in the former. For a region to reap the biodiversity benefits of intensification, and to concentrate agricultural production on already cleared lands, policy interventions like land zoning or product certification are needed. Agricultural intensification does not aggravate, and often mitigates, side effects like nitrogen pollution, soil erosion, and greenhouse gas emissions, on a per-unit production basis. Organic farming typically performs no better than its conventional counterparts in terms of pollution.

SUBSTITUTION AND INTENSIFICATION PASSIVELY PROTECT NATURAL HABITATS AND WILDLIFE. By providing cheaper and better alternatives to wildlife harvesting, and by allowing demand for food, wood, and other goods to be met on a smaller area, substitution and intensification passively protect wildlife and habitats. When there is no economic reason to exploit wildlife or land for material purposes, they can be spared from human use, satisfying the aesthetic and spiritual desires that underpin conservation. Passive protection largely explains why half of all land on earth is not actively used by humans: no profit could be made from converting these lands to agriculture and forestry, and conservation is therefore the "highest use" of the land regardless of any formal protection. Nature use-less is nature saved.

ABUNDANT MODERN ENERGY ENABLES DECOUPLING. Many forms of substitution entail higher consumption of modern energy, including the substitution of farmed for wild fish and meat, as well as synthetic for organic fertilizer. Agricultural intensification relies on energy-intensive fertilizers, pesticides, machinery, and irrigation. Although modern energy can spare land and wildlife, it has environmental consequences itself, in the form of greenhouse gas emissions and conventional air pollution. This trade-off can be mitigated by moving toward less-polluting energy sources.

PROTECTED AREAS HAVE A LIMITED CAPACITY TO REDUCE AGGREGATE GLOBAL HABITAT LOSS AND WILDLIFE DECLINE. Protected areas, which are intended to exclude some or all ecologically harmful human activities from an area by legal means, are often unable to compete with other economic activities like farming or logging. Most of the land under protected-area status is passively protected, such that the legal protection makes little net difference to land use or resource extraction. When opportunity costs emerge or grow after legal protection is established, governments often make protected areas weaker or smaller, or remove protection completely. In other cases where protection competes with economic interests, protected areas are often weakly enforced, possibly indicating limited willingness of local and national communities to forego economic opportunities. Protected areas can overcome these obstacles and make a difference to land use or resource extraction within their borders, but in these cases the ecologically harmful activities are typically displaced elsewhere. This means that even though protected areas can be important conservation instruments at the landscape level, their effects do not scale up to the global level as long as there is continued demand for crops, meat, timber, and other land-based commodities.

VALUING ECOSYSTEM SERVICES CAN ENABLE CONSERVATION AT THE LOCAL LEVEL, BUT DOES NOT SCALE UP TO ADDRESS GLOBAL HABITAT LOSS OR WILDLIFE DECLINE. Conservation by use, based on small-scale harvesting of ecosystem goods like fuelwood, wild foods, and rubber, often fails to alleviate poverty or compete with alternative land uses like intensive farming because of the very low incomes earned from harvesting these ecosystem goods. And even relatively low rates of harvesting cause some level of biodiversity loss. Regulating ecosystem services like air and water purification, pollination, and flood control can in many cases be performed by ecosystems far simpler than those typically targeted by conservation, and can in most cases be substituted or otherwise made redundant with technology. Even so, the per-unit area value of regulating ecosystem services from natural habitats may be able to compete with alternative land uses in cases where the regulating services are highly concentrated and where the natural habitats are sufficiently close to economic activities like farming or cities. However, it has not been proven that more diffuse regulating services, or those located far from cities or farmland, can compete on economic terms with nonconservation land uses like intensive farming, housing development, or tree plantations. Where valuing regulating services does alter land use, the economic activities, including farming and forestry, are typically displaced rather than eliminated, implying that this approach does not scale up to a global level.

CONTINUED AND ACCELERATED DECOUPLING CAN ALLOW HUMAN IMPACTS ON THE ENVIRONMENT TO PEAK AND DECLINE THIS CENTURY, BUT TRADITIONAL CONSERVATION APPROACHES WILL STILL BE NEEDED. Peak impact is not inevitable but rather depends on concerted action by governments, NGOs, and private actors. As such, decoupling offers a concrete goal and an affirmative vision for conservation in the 21st century. However, decoupling does not solve every conservation problem, and comes with its own limitations. Decoupling does not guarantee that the landscapes that conservationists care about most will be preserved, nor that land that remains in production will be concentrated in areas where ecological impacts are least significant. Even after peaking, large-scale environmental impacts will persist through the century. Decoupling can also be inadequate in cases where environmental harm is not directly linked to the production of an economic good, such as with harmful species introductions. Decoupling should therefore not be understood as an alternative to existing conservation approaches but as a complement that makes conservation possible on a larger scale. Decoupling addresses the limited capacity of protected areas and ecosystem services to achieve reductions in aggregate human impacts, whereas protected areas and ecosystem services, within a framework of strategic landscape planning, address the limited capacity of decoupling to achieve optimal outcomes at the species or landscape level.

A BROADER FRAMEWORK FOR CONSERVATION SHOULD INCLUDE ACTIVE DIFFUSION OF LOW-IMPACT TECHNOLOGIES, MODERNIZATION, LANDSCAPE PLANNING FOR PROTECTION AND PRODUCTION, AND INNOVATION ON THE TECHNOLOGICAL FRONTIER. Conservation organizations, governments, and private firms can actively contribute to accelerating decoupling by, among other things, supporting agricultural intensification and substitution away from wild fish and meat, as well as helping societies climb the energy ladder toward cleaner, cheaper, and less land-intensive energy sources. There are already examples of successful on-the-ground projects to increase crop yields and help communities transition away from fuelwood. These processes of substitution and intensification occur within the broader context of modernization, including urbanization, income and consumption growth, and a shift from subsistence farming to manufacturing and services. For example, agricultural intensification goes hand in hand with urbanization and off-farm employment. Urbanization, rising incomes, and increased availability of farmed meat can enable a transition away from hunting wild meat. Landscape planning includes the strategic design and placement of protected areas, infrastructure such as dams and roads, as well as farmland and production forest, in order to seize opportunities from decoupling and minimize biodiversity loss from production of food, energy, and other goods. Finally, innovation on the technological frontier in areas like agriculture and energy pushes forward the envelope of possibility for decoupling.

INTRODUCTION

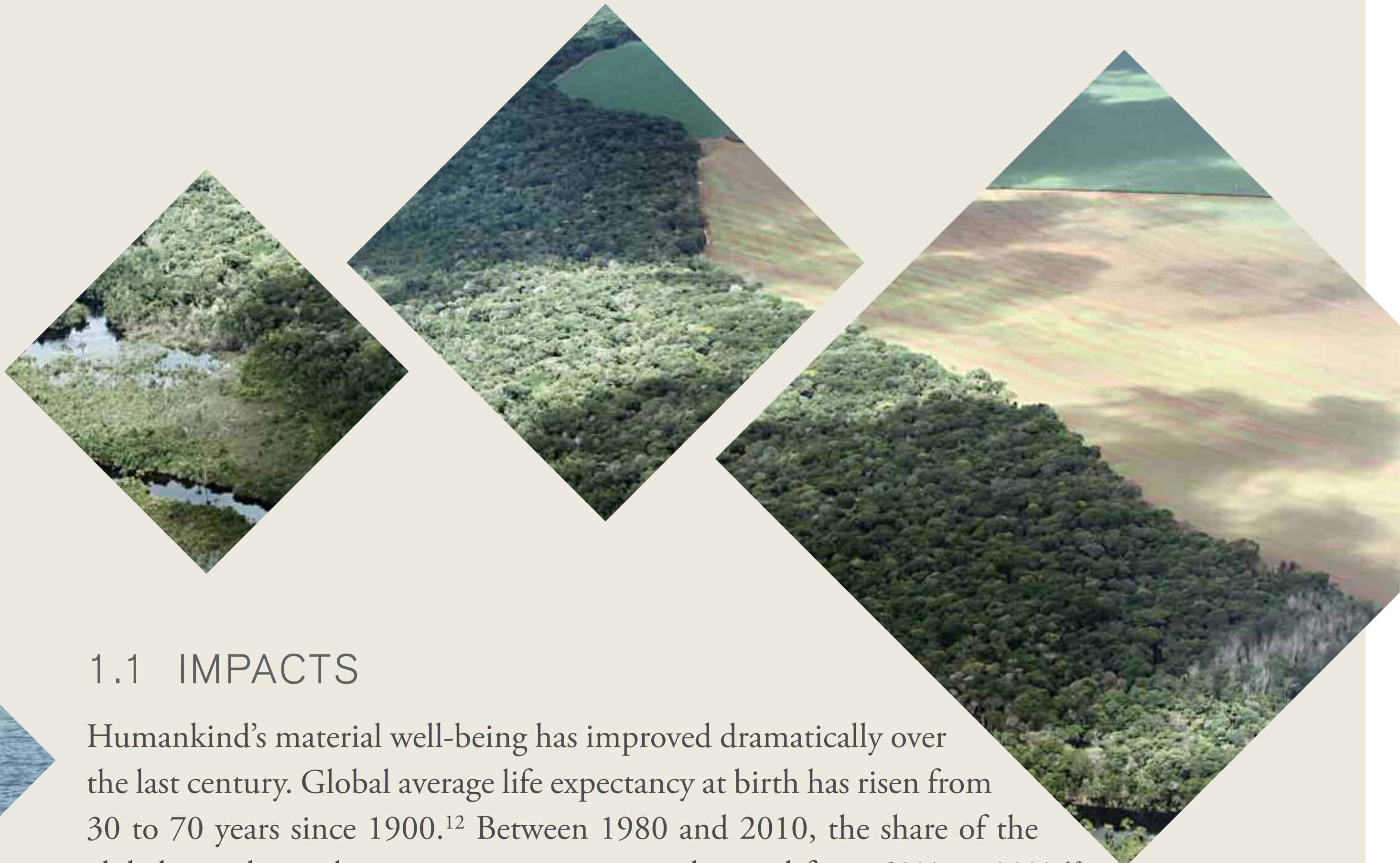
Over the last 40 years a growing body of scholarly research has documented the decoupling of economic growth from resource consumption and pollution. Economists have quantified how rising productivity and efficiency result in dematerialization, or fewer material inputs per unit of GDP.[1] Environmental scientists have tracked how several forms of air and water pollution have peaked and declined, alongside economic growth, in developed economies.[2,3] Systems analysts have developed substitution models to predict the speed at which new products and resources, including primary energy, would replace incumbents.[4,5] And agronomists have calculated how higher crop yields have significantly reduced land requirements for agriculture.[6,7]

Decoupling research has been increasingly taken up by policy makers and international organizations. In 2001, Organisation for Economic Co-operation and Development (OECD) environment ministers declared decoupling to be one of their highest priorities, and in 2002 published a set of 31 decoupling indicators.[8] In 2007, the United Nations Environment Programme (UNEP) started the International Resource Panel to investigate cases of resource decoupling.[9] The United Nations Intergovernmental Panel on Climate Change includes scenarios constructed from historical rates of decoupling carbon dioxide from energy consumption, and energy consumption from the economy, to produce scenarios of possible futures and to inform climate and energy policy.[10]

Decoupling has significant implications for conservation science and policy, but to date little has been done to explore how decoupling could be accelerated to safeguard biodiversity inside and outside of protected areas. *Nature Unbound* addresses this gap by assessing decoupling trends and processes and how they might inform conservation for the 21st century. While the focus is narrowly on what decoupling can do to protect wildlife and natural habitats, *Nature Unbound* argues for a wider vision of decoupling beyond resource substitution and productivity to include related processes such as urbanization. As such, *Nature Unbound* offers a new analytical framework for understanding how humans both destroy and save nature, and a normative scenario for accelerating decoupling and hastening the arrival of a global peak, and then decline, in aggregate human impacts on the environment.

Conservation in the 21st century will inevitably include trade-offs and hard choices. What decoupling offers is the promise of reducing the number and size of those trade-offs. Conservation science and practice have, over the past 50 years, evolved beyond biology and ecology to include a broader set of human concerns having to do with human well-being and economic development.[11] For decoupling to be useful to policy makers, conservation research will need to broaden even further. We hope *Nature Unbound* contributes to that process.

1. HOW HUMANS DESTROY NATURE



1.1 IMPACTS

Humankind's material well-being has improved dramatically over the last century. Global average life expectancy at birth has risen from 30 to 70 years since 1900.[12] Between 1980 and 2010, the share of the global population living in extreme poverty dropped from 50% to 20%.[13] On most measures of human well-being, developing countries have been converging with the developed world over the past few decades.[14] As the global population has more than quadrupled since 1900,[15,16] and global per-capita income has increased at least fivefold,[16] total consumption of economic goods like food, water, materials, energy, and living space has vastly increased.[17–21]

Human success has come at the direct expense of nonhuman species. Biodiversity loss is by and large a direct consequence of production of goods and services like food, water, materials, and energy.[22–24] We focus on four broad types of impact — physical interventions in the environment — which in turn cause biodiversity loss. These impacts are wildlife harvesting (eg, bushmeat, whales, wild fish, and fuelwood from natural forests), extraction of abiotic resources like water, land-use change (which causes habitat loss and degradation), and pollution (eg, emissions of greenhouse gases and agents of eutrophication and acidification).

Human success has come at the direct expense of nonhuman species.

A single economic good (like food) can be associated with multiple impacts (land-use change and nitrogen pollution), which in turn impact biodiversity in many ways. Conversely, a single impact, like land-use change, can be associated with several economic goods. Sometimes, the impact is one and the same as the biodiversity loss, for example in the case of wildlife harvesting. In other cases, impacts connect to biodiversity loss through a causal chain, as when emissions of greenhouse gases causes warming of the atmosphere, which in turn changes precipitation patterns, which in turn may impact biodiversity negatively.[25–27] In these cases, the amount of impact may not have a fixed or linear relationship to the amount of biodiversity loss.[25]

The past several decades have seen a great loss of nonhuman life. Between 1970 and 2010, populations of a large number of birds, mammals, amphibians, reptiles, and fish have declined by more than half globally.[28] The declines were most severe in the Neotropical region (South and Central America and the Caribbean), with an average decline of 83%, and the Indo-Pacific region (South and Southeast Asia and Oceania), with an average decline of 67%.[28] At least 128 birds and 61 mammals have gone extinct since 1500.[29] Today, 26% of mammals, 13% of birds, and 41% of amphibians are threatened with extinction,[30] and overall, their status is deteriorating.[31] Out of the 31 largest mammalian carnivores — including wolves, large cats, otters, bears, and hyenas — three out of five species are threatened and their ranges are on average less than half of their historical extent.[32]

1.2 WILDLIFE HARVESTING

Wildlife harvesting refers to the extraction of wild fauna and flora to supply goods like food and materials. This can have severe impacts on biodiversity. Early hunter-gatherers, seeking meat, fur, and other animal products, contributed to the extinction of more than half of the world's large terrestrial mammals from 50,000 to 10,000 years ago.[33–35] The repercussions of these extinctions are still felt, not only in the absence of the megafauna itself, but also in the ecological cascade effects that their extermination ushered in.[36,37]

> Hunting of wild animals for their meat is a major driver of faunal decline, especially in tropical forests.

Hunting of wild animals for their meat is still today a major driver of faunal decline, especially in tropical forests. William Ripple et al. deem hunting "likely the most important factor in the decline of the largest terrestrial herbivores."[38] More and more areas across Asia, Africa, and increasingly South America are suffering from the "empty forest syndrome," where populations of many mammals have been severely depressed or extirpated, that is, driven extinct locally.[39–42] In the Congo Basin, for instance, it is estimated that 60% of mammal taxa are hunted unsustainably, and that as much as five million tons of wild meat are harvested every year.[43]

Harvesting of wild fish has taken a large toll on marine and freshwater biodiversity. Today, nearly one-third of global fish stocks are overexploited,[44] and the abundance of marine fishes declined by 38% between 1970 and 2007.[45] Overharvesting of wild fish has led to numerous local extinctions of sharks, skates, sawfish, and other species.[46,47]

Whaling resulted in a dramatic decline in whale populations. In the 19th and 20th centuries, whales were hunted for their oil (used for lighting, margarine, soap, lubrication, and other goods), as well as for their meat.[48] At the peak of whaling around 1960, up to 75,000 whales were killed annually. The total number of whales killed in the 20th century was nearly three million.[49] Blue whales, the largest animals on earth, were reduced to a few percent of their pre-whaling levels.[50]

Hunting of birds and mammals for medicinal and ornamental uses has taken a heavy toll on many species. Rhinoceroses, tigers, sun bears, and several other species are frequently used in traditional Chinese medicine.[51] Elephants are hunted for their ivory.[52] While the extent of unsustainable wildlife harvesting for medicinal or ornamental uses is hard to know with any certainty, a 2014 study estimated that as much as 6% to 8% of the African elephant population was killed illegally every year between 2010 and 2012, leading to a decline in the overall population.[52] Illegal hunting reduced the population of black rhinos by 98% between 1960 and 1995; the population has since recovered somewhat but is still only at around 10% of historical levels.[53] Hunting of tigers driven by demand for traditional medicine contributed to a 41% contraction in the geographical range of tigers in the decade leading up to 2007.[54]

Extraction of wood from natural forests for use as fuel or for production of charcoal is a major driver of forest degradation and deforestation. It accounts for nearly one-third of forest degradation in the tropics and subtropics worldwide; for tropical and subtropical countries in Africa, the share is about 50%.[55] Helmut Geist and Eric Lambin found wood harvesting for domestic uses to be implicated in 28% of tropical deforestation, based on 152 case studies.[56] Many tropical biodiversity hotspots are located in poor regions where a large proportion of the population relies on fuelwood for domestic heating and cooking. In the Brazilian Atlantic forest — one of the world's most threatened biomes — fuelwood harvesting has been estimated at over 300,000 tons per year, equivalent to 1.2 to 2.1 thousand hectares of tropical forest.[57] Forest cutting for fuelwood has been identified as the greatest driver of forest loss and attrition in India, where nearly 100 million tons of fuelwood are harvested annually.[58]

1.3 LAND-USE CHANGE

Humans today actively use nearly half of the earth's ice-free land.[59] Most of that area is used for growing biomass, while only a small proportion (0.5% to 3%) is for cities.[60–66] Biomass production can be broken down into three categories: pasture (3.4 billion ha or 26% of global ice-free land according to FAO data[67]), cropland (1.6 billion ha or 12% of global ice-free land[67]), and production forest (1.2 billion ha of production-designated forest, or 9% of global ice-free land, of which 0.26 billion is planted forest[68]). Cropland and pasture have replaced more than 20% of all forests, nearly 60% of savannas and grasslands, and about 50% of tropical and temperate deciduous forests worldwide.[69]

Humans actively use nearly half of earth's ice-free land, primarily for farming, which displaces and fragments natural habitats.

Each of the three categories of biomass production generates a large variety of goods. Cropland is used to produce crops for direct human consumption, as well as for animal feed. Around 55% of global crop production by calorie content is for direct human consumption, and 36% is for animal feed.[70] The remainder is for the production of non-food goods like fiber (35 million ha[67]), biofuels (around 25 million ha[63]), chemical feedstocks, and organic fertilizer. Production forest generates industrial roundwood used for pulp or building material for example, and biomass for energy production. Production forest also includes rubber plantations, which today cover about 10 million ha worldwide, mostly in Southeast Asia.[68]

Human land use causes biodiversity loss by reducing, degrading, and fragmenting habitat for species. Two important processes that contribute to this are conversion and intensification. Conversion refers to a wholesale change in land cover, such as when forest or shrubland is replaced with pasture or cropland. Intensification involves a gradual loss of biodiversity through, for example, elimination of patches of natural habitat interspersed with farmland, production forest, or built-up land, or in the case of biomass production, higher densities of the target crop, increasing application of fertilizer and pesticide, or increasing cropping frequency. Conversion and intensification together make land-use change the single biggest pressure on global biodiversity.[71–73]

1.4 EXTRACTION OF ABIOTIC RESOURCES

Humans extract large quantities of abiotic (non-living) resources, including metals, construction minerals, hydrocarbons, and water. The depletion of most of these resources does not constitute an impact on biodiversity per se. Most species and ecosystems do not suffer from reduced amounts of metals or hydrocarbons since they do not depend on them in the first place. Mining, quarrying, or hydrocarbon extraction create pressures on biodiversity through pollution and land use, not scarcity as such.

Excessive freshwater extraction, both from surface sources (lakes and rivers) and from underground aquifers, can harm freshwater-dependent species and ecosystems.[74] One study estimates that extraction for human uses is already impinging on freshwater ecosystems in more than half of the 405 assessed river basins.[75] Several major rivers, including the Colorado River, run dry before they reach the ocean — severely harming downstream ecosystems.[76] Groundwater depletion affects major regions in North America, North Africa, Australia, and elsewhere.[77] Human use and management of water causes biodiversity loss not only through scarcity, but also through land-use change and resultant habitat loss, for example from damming rivers or draining wetlands for conversion to agriculture. In some cases, the distinction between the two pressures — water scarcity and land-use change — can be ambiguous, as in the case of wetland drainage.

1.5 POLLUTION

Pollution is defined here as substances, released at any point in the production process, that have the capacity to harm human and nonhuman life. Pollution encompasses a wide range of effects, including toxicity, acidification, eutrophication, and global warming. Toxic agents include heavy metals (eg, lead and mercury), radioactive residues, and persistent organic pollutants (eg, PCB and DDT), which can cause direct mortality or lower reproductive fitness in plants and animals.

Acidification and eutrophication harm species and ecosystems on land and in the sea. Acidification occurs through atmospheric deposition of acidifying substances ("acid rain"), particularly reactive sulfur and nitrogen compounds from fossil fuel combustion and agriculture, which harms soils, freshwater ecosystems, and forests. Ocean acidification occurs through uptake of carbon dioxide by the oceans, harming marine ecosystems, for example through its effects on calcifying organisms.[78] Eutrophication is primarily caused by reactive nitrogen and phosphorous from agriculture and fossil fuel combustion, either leached into lakes and rivers or deposited from the atmosphere.[79,80] Eutrophication can alter species compositions in lakes and rivers, grasslands, and other ecosystems, and can also create toxic algal blooms, hypoxic (oxygen-free) conditions in the coastal ocean and freshwater systems, and other impacts on ecosystems.[80] Deposition of nitrogen and sulfur is estimated to exceed critical loads for acidification and eutrophication in up to one-fifth of the terrestrial biosphere.[79] Coastal "dead zones" now cover more than 245,000 km^2 worldwide.[81]

Global warming is primarily caused by carbon dioxide emissions from fossil fuel combustion and land-use change, and has a range of possible impacts on ecosystems, including shifting species distributions and inundation of coastal habitats.[82–85] Finally, ecosystems can suffer from excessive near-surface ozone, caused primarily by nitrogen oxides, methane, and carbon monoxide, or depleted stratospheric ozone and the associated increase in ultraviolet radiation at earth's surface, caused by emissions of chlorofluorocarbons and other ozone-depleting substances.

2. HOW HUMANS SAVE NATURE

2.1 THEORETICAL OVERVIEW

DECOUPLING: RELATIVE AND ABSOLUTE

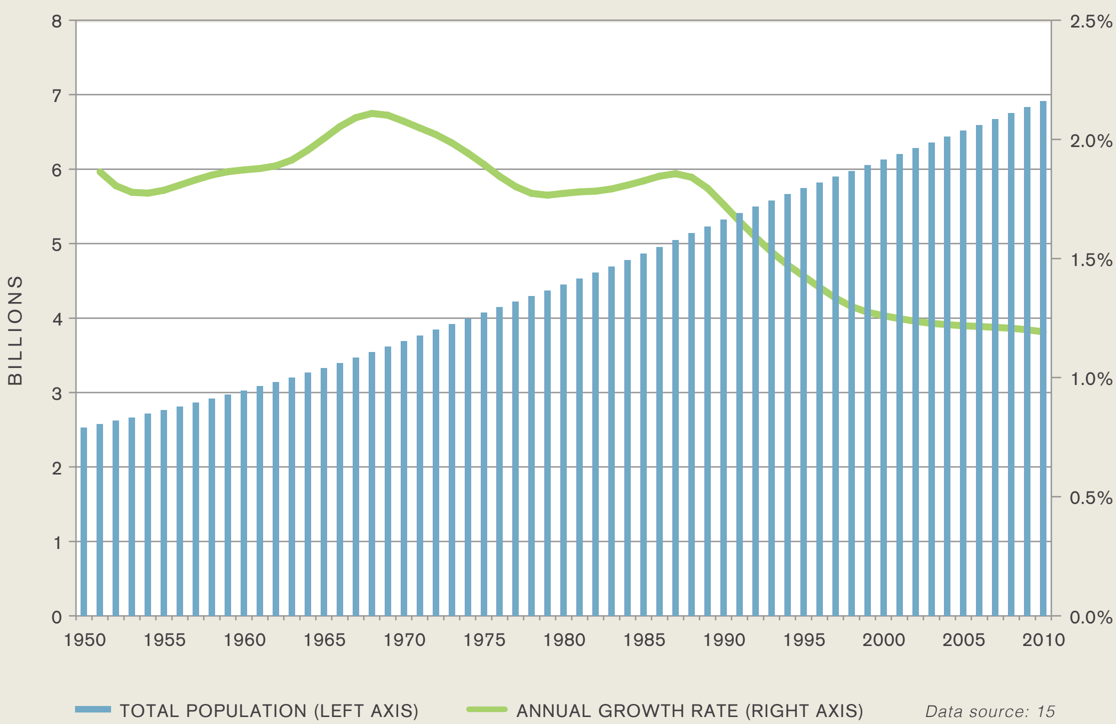
While many of humankind's environmental impacts have grown in absolute terms, several have started to flatten out or even decline. Per-capita impacts have for the most part gone down. Nearly all forms of land use, wildlife extraction, water consumption, and pollution have been declining on a per-capita basis for decades, and in some cases for centuries.

This process is known as decoupling. *Relative* decoupling refers to impacts growing at a slower rate than population or total consumption. *Absolute* decoupling means impacts are declining in absolute terms. Absolute decoupling can occur alongside rising consumption. For example, if demand for a good grows 2% per year while the technology factor improves 4% per year, the total impact will shrink by about 2% every year, so that in 33 years the impact will be halved.

DRIVERS: POPULATION, CONSUMPTION, AND TECHNOLOGY

Human impacts on the environment can be decomposed into three drivers: population, average per-capita consumption, and a technology factor.[86–88] Consumption is measured in terms of services like nutrition (kcal), heat (Btu), light (lumens), or transportation (eg, passenger miles). Consumption is not a modern phenomenon. Hunter-gatherers consumed food, water, and energy, just as people do today. The difference is one of scale. Total consumption, or demand, is the product of population size and average per-capita consumption. The technology factor represents the amount of environmental impacts per unit of goods and services, such as the amount of land per calorie of food, or the amount of carbon emissions per unit of energy.

WORLD POPULATION



Data source: 15

All three drivers have contributed to the slowing growth of total impacts. Global population growth peaked around 1970 at about 2.1% per year, and has since declined to around 1.2% (Figure 1).[15] Per-capita consumption of goods like food, energy, materials, and water can grow fast in rapidly developing countries, but grows more slowly or saturates completely at later stages of development, as more and more economic activity is directed toward less materially intensive services.[1,19,89]

Nearly all forms of land use, wildlife extraction, water consumption, and pollution have been declining on a per-capita basis for decades, and in some cases for centuries.

How soon and at what level demand saturates varies between goods. At one end of the spectrum, per-capita food demand saturates relatively quickly.[90] A country with a per-capita income of $30,000 typically consumes no more food than a country half as rich.[90] At the other end, demand for energy in general and electricity in particular can continue growing even at relatively high income levels.[91]

While population and per-capita consumption have added, albeit increasingly slowly, to the overall burden on the environment, the technology factor has reduced it. Although the technology *factor* is a simple efficiency ratio, technology more broadly consists of tools and the skills, knowledge, and infrastructure associated with them.[92,93] In this sense, technology is as old as *Homo sapiens* itself. Early Holocene subsistence farming is no less technological than industrial agriculture today. In the words of Joseph Huber, technology is the "immediate ecological factor in human society besides the fact of humans' sheer biological existence."[93] Therefore, just as the destruction of nature always involves technology, sparing nature is ultimately about technology too.

REBOUND

Improved production efficiency often results in rebound, whereby energy, resource, and cost savings associated with more-efficient technologies results in increased rather than reduced consumption.[94,95] In a sense, present-day population and consumption levels were made possible by such rebound resulting from the more efficient use of natural resources. Had our agricultural, energy, and transportation technologies not improved dramatically over centuries, the human population would probably be significantly smaller and poorer.

For most if not all material goods, however, demand eventually saturates. Increased efficiency will only lead to increased consumption so long as demand remains unsaturated. In this sense, rebound and demand saturation are two sides of the same coin. Efficiencies both drive increased production until such time as demand saturates *and* compress the timeframe in which saturation is achieved. Once demand for a given resource has saturated, more-efficient technologies can drive declining demand for that resource.

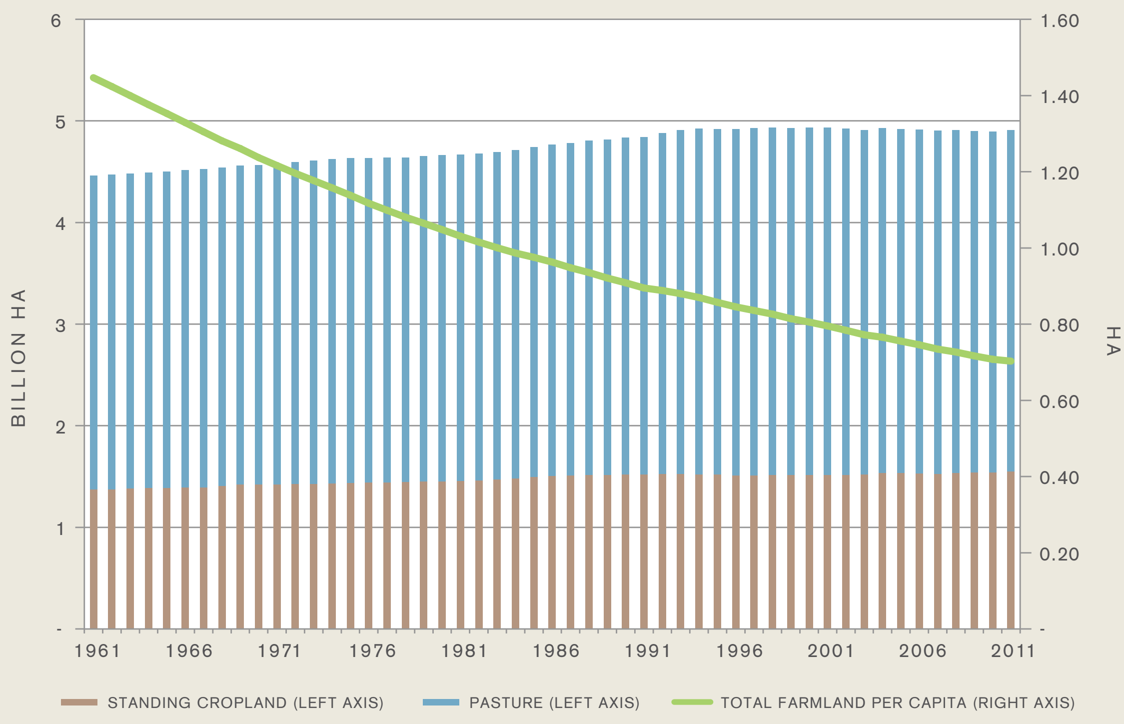
2.2 IMPACT TRENDS

The degree to which demand saturation and the technology factor offset a growing human population and rising consumption depends on the type of economic good. In this section, we review the empirical evidence for these trends.

FOOD

While food production is rising globally, demand is saturating in middle- and high-income countries. Global food supply, measured in calories per day, has nearly tripled over the last five decades, outpacing population growth. As a result, food supply per capita has gone up by over 30%.[15,17] Meat consumption, which requires more land per calorie consumed, has more than doubled on a per-capita basis.[17] Amidst this overall increase, however, there is strong evidence of demand saturation. The largest increases in food supply per capita occur in low- and lower-middle-income countries, and once countries reach a GDP per capita of around $12,500, food supply and dietary composition stabilize.[90] Per-capita food supply has remained virtually flat in Western Europe for over 20 years; in the United States, it was slightly lower in the last year on record (2011) than in the mid-1990s.[17] Furthermore, much of the increase in meat consumption has been in the form of chicken, which is four times more efficient than pork and eight times more efficient than beef in terms of converting feed protein into food protein.[70,96] Demand for beef has in fact remained relatively stable over the last several decades, having risen somewhat in developing countries like China and Brazil, but fallen slightly in many other regions, including North America, Oceania, and Europe.[17,96]

GLOBAL FARMLAND AREA



Increases in per-capita food consumption have been more than offset by increasing agricultural efficiency, such that farmland per capita has gone down (Figure 2).

The global amount of cropland per capita went from 0.44 ha in 1961 to 0.22 ha in 2011, and pasture went from 1.0 to 0.48 ha per capita.[15,67] (The cropland figure includes crops used for biofuels, which increased from 1% to at least 4% of global crop calories from 2000 to 2010.[70]) The total amount of land used for food production (the sum of cropland and pasture) per capita therefore declined by more than half. In absolute terms, global cropland area increased by 13% between 1961 and 2011, and pasture increased by 9%.[67] Yet all of the increase in the total farmland area (cropland and pasture together) occurred before the mid-1990s. Between 1995 and 2011, the total area under cropland and pasture remained virtually flat — during a period in which global population grew by more than 20% and GDP per capita nearly doubled.[13,15,67]

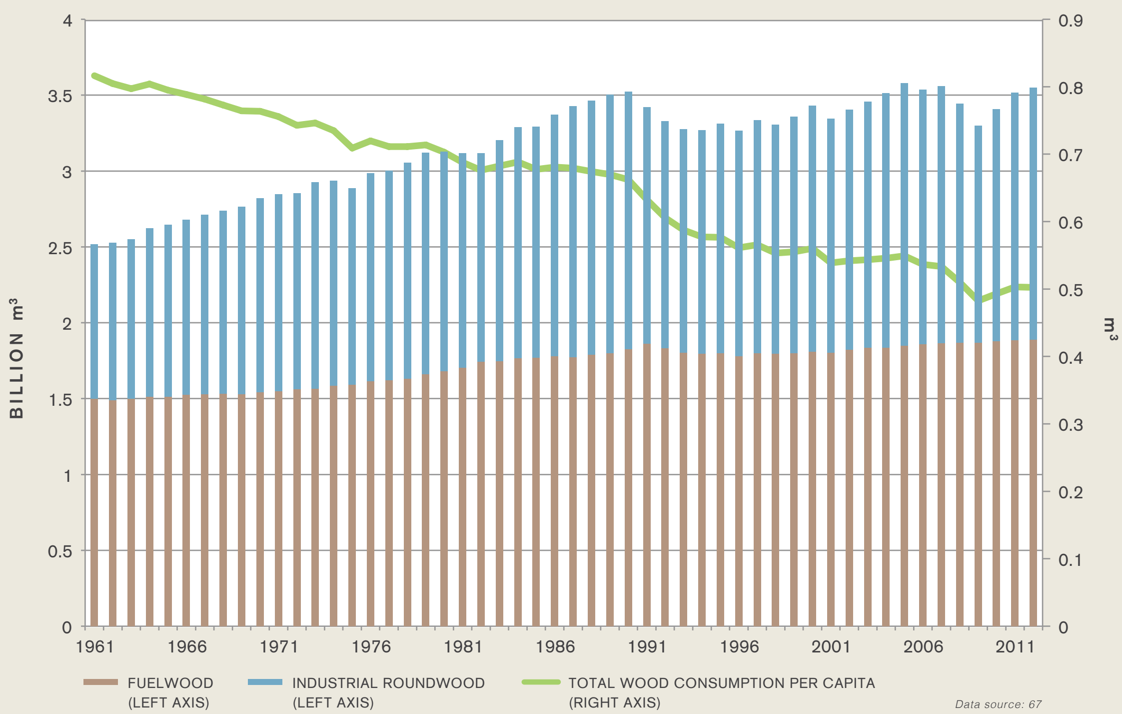
Countries can go through the entire dietary transition without expanding the area requirement of crop production per capita. Thomas Kastner et al. calculated the cropland requirement for each of 17 world regions, accounting for imports and exports.[97] In every one of these regions, the per-capita cropland requirement (including crops for direct consumption and crops for livestock feed) declined over the past five decades, implying that agricultural efficiency has offset changes in diet in rich and poor regions alike. In fact, the per-capita cropland requirement is about the same in Northern Europe, which has rich diets and high yields, as it is in much of Africa, where diets are poor and productivity low.[97]

Three key trends have contributed to the agricultural productivity improvements seen over the past half century. First, overall crop yields — defined as crop output per harvest — increased by 87% between 1965 and 2005, or about 2.2% per year, noncompounding.[98] Second, the average number of harvests per year increased too — from 0.78 harvests per year in 1961 to 0.89 in 2011, a 14% increase.[99] Finally, the efficiency of poultry, beef, and pork production has increased.[100,101] In the United States, the amount of feed needed to produce 1 kg of broiler chicken has declined by about 60% since the mid-1930s.[102] Producing 1 kg of beef in the United States required 19% less feed in 2007 than in 1977.[103]

WOOD

Global consumption of wood has plateaued (Figure 3). Wood is used for two broad purposes: wood fuel, especially in poor countries, and industrial roundwood, used for example as construction material and pulp. Of the 3.5 billion m^3 of wood harvested globally in 2012, wood fuel accounted for 53%.[104] As countries modernize, their consumption of wood tends to go from majority wood fuel to majority industrial roundwood. Total per-capita consumption of wood is about the same in Africa and in North America, but the share of wood fuel is 90% in Africa and only 21% in North America.[104] Globally, consumption of industrial roundwood increased by more than half between 1961 and the mid-1980s but has since fluctuated without exhibiting any clear upward or downward trend.[104] Thus, in the past 50 years, the amount of industrial roundwood per capita fell from about 0.33 m^3 to about 0.24 m^3, a decline of 29%. Consumption of wood for fuel increased, in absolute terms, by less than one-quarter from 1961 to 1990, remained flat until 2000, and increased only marginally since then.[104] Global per-capita consumption of wood fuel has dropped by nearly half in the last 50 years.[104]

GLOBAL WOOD CONSUMPTION



Data source: 67

Saturating global demand for industrial roundwood and wood fuel, together with an increasing share of wood coming from high-yield plantations, allowed the total forest area dedicated for production to decline by about 50 million ha between 1990 and 2010, an area nearly the size of France.[105–108] In the mid-20th century, nearly all wood harvests were from natural forests, but since then an increasing proportion comes from managed forests or tree plantations.[109] The amount of wood extracted from natural forests peaked around 1989 and has since declined markedly, indicating reduced pressures on natural forests.[109]

BUILT-UP LAND

The simultaneously occurring trends of urbanization in developing countries and suburbanization in developed ones make it difficult to assess the net change in the land area for settlement and infrastructure. On the one hand, urbanization itself is likely to be land sparing because villages overall have lower population densities than cities.[110] For instance, villages in China have a population density a little over one-quarter of the average of large cities in the Eastern Asia and Pacific region.[111,112] On the other hand, cities are overall becoming less dense — between 1990 and 2000 urban land cover expanded at more than twice the rate of urban population growth.[21,65] This was true for developing as well as developed regions and can be explained, at least in part, by increasing incomes, which allow for larger houses and proportionally larger areas for public facilities, gardens and parks, and shopping areas.[21,65] Thus average urban population densities in developing countries are higher than in developed countries.[65]

HUMANKIND'S TOTAL LAND FOOTPRINT

Adding up the areas of cropland, pasture, production forest (from FAO[67]), and built-up land (from Liu et al. 2014[64]) yields a total land footprint of about 0.9 ha per capita. That can be compared with an estimated average land clearing of 4 ha per capita among early agriculturalists about 7,000 years ago.[113] In terms of land actively used — and natural habitat displaced — humans today tread more lightly on the land than anytime in the past several thousand years.

WILDLIFE HARVESTING

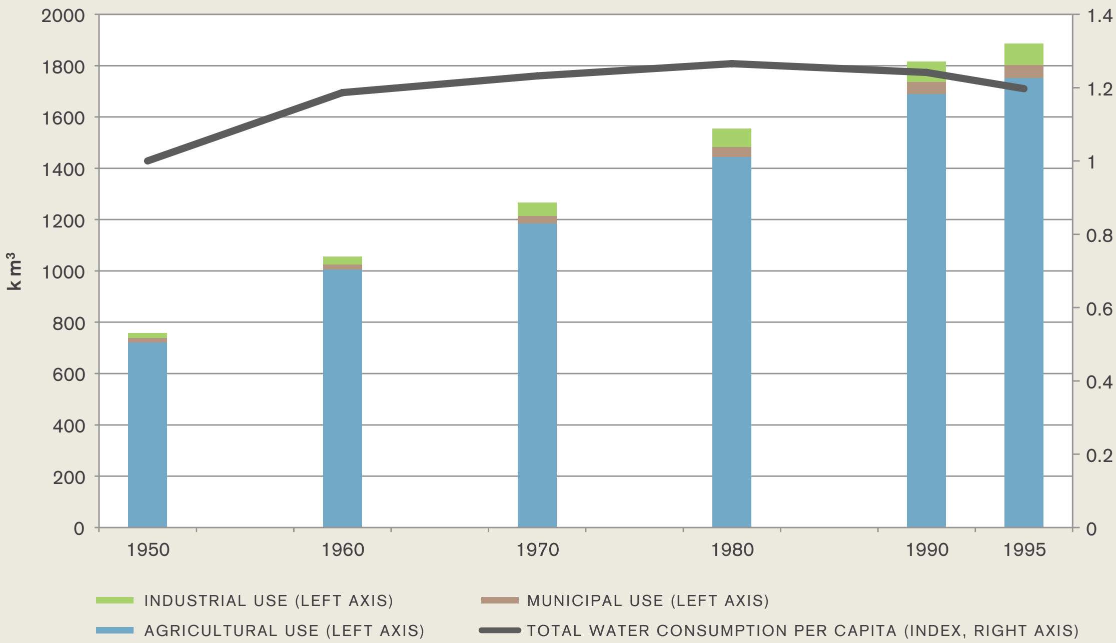
Much of the world has or is decoupling from overharvesting of wild animals for meat, which is today mostly confined to lower-income countries and populations, especially in tropical regions. In the tropics, harvesting of wild animals for meat is thought to have increased dramatically in recent years.[41] As for harvesting of wild animals for medicinal and ornamental uses, the killing of African elephants is at the highest level in 20 years,[114] with a marked increase around the year 2010.[115] Killing of rhinos has also increased recently. In South Africa, home to nearly three-quarters of wild rhinos in the world,[116] the number of rhinos poached went from 7 in 2000[117] to 1,215 in 2014.[118] Rates of tiger poaching and trafficking in India increased in the three decades up to 2000 but appear to have remained stable since then.[119]

The world has largely decoupled from whale harvesting. Since 1985, average annual catches are less than 2,000, a tiny fraction of the nearly 75,000 whales caught annually around 1960.[49,120] Global wild fish harvests increased up to the mid-1980s; concurrently, the percentage of stocks fished at a biologically unsustainable level increased from 10% in 1974 to 26% in 1989.[44] Since then, total harvests have stayed flat, and the number of stocks fished at unsustainable levels has grown marginally, to 29% in 2011.[44]

WATER

Efficiency gains were able to more than offset increasing per-capita demand for water-using goods and services in the last decades of the 20th century. According to the most comprehensive dataset available, global water consumption — the portion of water use that is not returned to the original water source after being withdrawn — went from 768 km^3 to 2,074 km^3 between 1950 and 1995, an increase of about 170% (Figure 4).[18] Per-capita water consumption increased by 27% between 1950 and 1980, but then declined by about 5% in the following 15 years.[18]

GLOBAL WATER CONSUMPTION



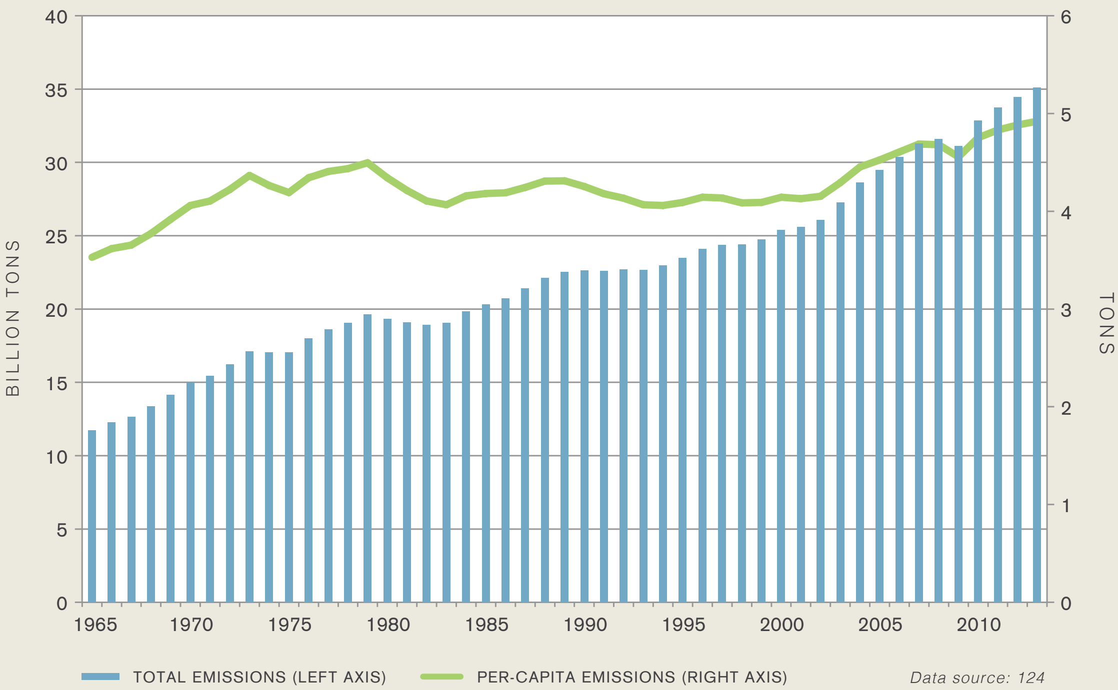
Data source: 18

Whereas total water consumption in agriculture went up by 70% between 1961 and 2009, the amount of water needed for an average global diet has, according to a study by Chen Yang and Xuefeng Cui, declined by nearly one-quarter in the same period. This occurred in spite of diets shifting toward more water-intensive meat products.[121] This drop is explained by very significant improvements in agricultural water efficiency.[121] The pattern of declining per-capita water requirements for food production held for all of 18 world regions but four (North Africa, West Africa, Eastern Asia, and Southern Europe).[121]

Per-capita municipal and industrial water use increased between 1950 and 1980, but remained flat, and declined, respectively, until 1995.[18] It should be noted that aggregate global water consumption is an imperfect proxy for global impacts on ecosystems from human-caused water scarcity, which depend crucially on the spatial and temporal distribution of water consumption, as well as other local factors.[122]

GREENHOUSE GAS EMISSIONS

GLOBAL CARBON DIOXIDE EMISSIONS FROM ENERGY



Data source: 124

Greenhouse gas emissions are far more coupled to economic development than the other trends reviewed here, even as emissions per unit of energy have declined. More than three-quarters of greenhouse gas emissions from human sources were accounted for by carbon dioxide in 2010; the remainder chiefly includes methane and nitrous oxide.[123] Fossil fuel combustion accounted for 86% of all anthropogenic carbon dioxide emissions.[123] The remaining 14% of carbon dioxide emissions come from land-use change, a proportion that has declined from 24% in 1970.[123] Carbon dioxide emissions from fossil fuels, used in the production of energy, have risen by about 2.3% per year globally between 1965 and 2013 (Figure 5).[124] This growth rate implies a doubling of emissions every 30 years.

Growth in carbon dioxide from energy production can be decomposed into two factors: per-capita energy demand, and carbon intensity of energy (carbon emissions per unit energy). The former has tended to increase along with per-capita incomes in low- and middle-income countries, but has tended to increase more slowly, if at all, in high-income countries.[91] Carbon emissions from energy production have not risen quite as fast as primary energy consumption, which means that there has been a slight improvement in the amount of greenhouse gas emissions per unit energy. This ratio declined by about 13% between 1965 and 2000 but has since risen slightly.[124] This rise has been attributed in large part to rapidly rising energy consumption and relatively high carbon intensity of energy in China.[125]

Global per-capita carbon dioxide emissions, the product of per-capita energy consumption and the carbon intensity of energy, have increased in recent decades, by nearly 40% between 1965 and 2013.[124] While per-capita emissions in rich, OECD (Organisation for Economic Co-operation and Development) countries have remained relatively flat since 1980, they have gone up by more than 60% in non-OECD countries during the same period.[126]

POLLUTION

Other forms of pollution are both rising and falling, with evidence for both relative and absolute decoupling. While a comprehensive account of trends in emissions of pollutants is beyond the scope of this report, some broad trends are observable. Out of four key airborne agents of terrestrial acidification and eutrophication, one has peaked in absolute terms globally (sulfur dioxide), two appear to have plateaued (nitrogen oxides and nitrous oxide), and only one is still rising (ammonia).[127,128] Emissions of ozone-depleting substances, chiefly CFCs, have fallen steeply from their peak in the late 1980s.[128] Emissions of ground-level ozone precursors have declined substantially in Europe and the United States, while increasing in developing regions like East Asia.[129,130]

Although overall trends in emissions of toxic substances are difficult to assess, UNEP (United Nations Environment Programme) observes that conventional toxic pollutants are declining in many industrialized areas.[128] Atmospheric concentrations of many persistent organic pollutants recorded at Arctic monitoring stations have declined in recent decades, though this trend has been reversed in some cases, as with PCB.[131]

2.3 DECOUPLING MECHANISMS

DEFINITIONS

For wildlife harvesting and land use, two interrelated processes — substitution and intensification — explain the vast majority of improvements in the technology factor.

SUBSTITUTION refers to the replacement of one technology, or set of technologies, by another. Substitution can involve a change in production method — such as when rubber is produced from petroleum rather than rubber trees, when meat is produced with livestock rather than hunted in the wild, or when energy is produced with nuclear or solar instead of biomass. It can also involve a change in the very material itself — such as when steel or concrete replace wood as construction materials, or when synthetic fibers like nylon replace natural fibers like cotton.

INTENSIFICATION refers to improvements in land efficiency, measured as goods produced per hectare. Increasing yields in farming or forestry, as well as denser settlements, are examples of intensification.

PASSIVE PROTECTION

Substitution and intensification save or "spare" nature through what we call passive protection.[132,133] When better and cheaper substitutes exist for wildlife, the wildlife loses its economic value — there simply is no economic rationale for exploiting it.[134] It is passively protected. Both substitution and intensification also contribute to passive protection of land, or "land sparing." They do so by enabling land-intensive goods — primarily biomass in different forms — to be produced in a smaller area. When synthetic fertilizer replaced organic, the pressure to convert new lands into agriculture lessened. Higher yields on existing farmland — intensification — tend to lower prices of agricultural commodities, making new conversion less profitable, or not profitable at all.[133,135] It can also lead to abandonment of marginal agriculture, with attendant opportunities for habitat restoration and rewilding.[136] When there is no economic reason to exploit wildlife or land for material purposes, it can be left alone, satisfying the aesthetic and spiritual desires that underpin conservation. Nature use-less is nature spared.

Passive protection largely explains why half of all land on earth is not actively used by humans: no profit could be made from converting these lands to agriculture and forestry, and conservation is therefore the "highest use" of the land regardless of any formal protection.

Passive protection largely explains why half of all land on earth has *not* been converted to human uses. This includes a large proportion of the Amazon basin and the boreal forest. It also includes much of the land covered by protected areas — some 15% of the terrestrial ice-free surface.[137] The reason the land-use glass is half full is that no profit could be made by converting the land to agriculture or forestry.[138] Areas where high economic returns can be had are, for the most part, converted and actively used.

> When there is no economic reason to exploit wildlife or land for material purposes, it can be left alone, satisfying the aesthetic and spiritual desires that underpin conservation.
> Nature use-less is nature spared.

Two contrasting examples illustrate the principle of passive protection. Lowland rainforests in Southeast Asia over the past decades have been widely deforested. No wonder: each hectare can be worth over $20,000 when logged and converted to oil palm plantations.[139] At the other end of the spectrum, Russell Mittermeier et al. reckon the land values in many biodiversity-rich wilderness areas of the world are about $10 per ha.[140] The implicit price of a hectare of land bought as part of the Debt for Nature Swap initiative of the 1980s and 1990s was around $5 per ha.[141] Conservation International bought a conservation concession in Guyana at $1.25 per ha per year.[142] Land values this low are indicative of passive protection.[141] In other words, with or without formal protection, these areas would likely have remained intact. Conservation is the economically rational "highest" use of the land. Half the world's land surface is passively protected simply because we don't need it for any material purpose; it doesn't make commercial sense to convert it.

SUBSTITUTION: A FRAMEWORK

There are three very broad forms of production of material goods like food and energy: wildlife harvesting (eg, bushmeat or wood fuel harvesting in natural forests), controlled production of biomass (including most forms of agriculture and forestry), and fully synthetic production (eg, synthetic rubber and fertilizer). Each has its own set of environmental impacts. Yet, as we describe below, controlled biomass production tends to have lower overall environmental impacts per unit of goods produced than wildlife harvesting, and fully synthetic production has lower impacts still. This suggests that transitions up this "technology ladder" toward more artificial means of producing material goods leads to less and less harm to nature.

These broad substitution processes occur within the context of human development and modernization, and are broadly recognizable across regions and over time, but not in strictly temporal, absolute, or uniform ways. For example, whereas the direct reliance on ecosystems for material goods dominated the hunter-gatherer phase of human history, humans in agricultural, industrial, and postindustrial societies still often depend on wild animals, in particular fish, for food. In many societies, different modes of agricultural production exist simultaneously. Moreover, the transitions are often not absolute, or complete, and do not need to be in order to save or spare nature. As we will describe below, aquaculture need not entirely replace wild fish consumption to significantly reduce pressure on fish stocks and marine biodiversity. Finally, these transitions are always shaped by culture, politics, society, geography, and many other factors, making each case unique in important ways.

Wildlife harvesting entails the direct reliance on virtually unmodified ecosystem goods like bushmeat and wild fish. This is also the oldest form of obtaining economic goods from nature, dominating during the hunter-gatherer phase of human history, but lingering past the emergence of agriculture to this day in various forms. Wildlife harvesting is the most direct, and often most severe, way in which humans destroy nature by the large-scale killing of the subjects of conservation like wild animals. Wild meat harvesting alone can be a larger threat to mammals in tropical forests than habitat loss,[38] even if habitat loss is a bigger threat to biodiversity at the global level.[143] The transition away from reliance on wild fauna and flora is the most direct and often most significant way in which humans spare nature. Allowing for the continued existence, and return, of wild flora and fauna requires substitutes that reduce human demand for wild fish and mammals for protein, wood from natural forests for fuel, and so on.

The next technological form of production involves producing biomass under controlled forms, where the plants and animals in question are often highly modified and grown in highly technological systems, as in modern crop production, feedlot meat production, or aquaculture. This entails environmental impacts, most importantly land-use change, but it avoids the outright killing of the subjects of conservation, as in wildlife harvesting.

The goods produced in these systems cannot be understood as ecosystem services in themselves, but rather as techno-ecological hybrids, where much of the value of the final products is accounted for by technology and human labor.[144] Crops produced in industrial agriculture are far removed from any natural counterparts. Similarly, modern livestock are no more "ecosystem services" than are pet dogs, and are better understood as a technological substitute for bushmeat.

Ecosystem services continue to play a role in modern biomass production, where, for example, they contribute to the maintenance of productive soils, crop pollination, pest control, and stable provision of clean water.[145,146] These services constitute what are known as "regulating ecosystem services," whereby ecosystem services are inputs to the material goods produced but do not constitute the goods that humans consume themselves.

The third and final stage is what we might call fully synthetic. This includes things like synthetic rubber, fiber, and fertilizer. This stage too has environmental impacts

— especially in the form of pollution — but it largely avoids the most severe forms of impact, wildlife harvesting and land use.

Although moving from wildlife harvesting to controlled biomass production to fully artificial means of providing human material welfare involves reduced pressures on nature per unit of production overall, impacts are by no means altogether eliminated. Often, one kind of impact replaces another. Sparing forests from being converted to rubber plantations requires petroleum consumption that creates conventional air pollution and carbon emissions. As such, there is no free lunch — each instance of substitution will come with some degree of trade-offs. Even though these transitions reduce environmental impacts, they do not eliminate the need for societies to make what are often difficult choices about how to balance environmental costs and benefits.

Substitution can radically reduce human pressures on biodiversity, but significant pressures will persist. Even the most optimistic scenarios for substitution still involve significant use of land globally, primarily for farming, forestry, settlement, and infrastructure. There is currently no complete substitute for land in large-scale production of food and wood.[147] While the growth in global demand for wood may be slowing down,[104] it will remain significant for the next several decades. Food demand is projected to increase substantially over the next half-century as populations grow and get richer, and crop demand even more so, as the proportion of meat in the diets of developing countries rises.[148] A larger global population also means that more space will be needed for settlement and infrastructure.[112]

THE ROLE OF ENERGY

Moving up this technology ladder requires higher inputs of modern energy. Replacing organic with synthetic fertilizer saves a lot of land, but requires more energy.[149] The same applies to synthetic and natural rubber. Intensive livestock operations require large energy inputs for heating, feeding, lighting, and so on[150]

— but they take pressure off wild animals. Intensive aquaculture operations require large amounts of energy,[151] but can take pressure off wild fish populations. Higher crop yields which have spared large amounts of habitat from conversion have only been possible by large inputs of energy in the form of synthetic fertilizer, machines, irrigation systems, and so on.[152] In fact, agricultural efficiency has vastly increased on all accounts except for energy, of which it takes more today to produce a given amount of food than it did in traditional farming systems.[153–155] There are reasons to believe that it is precisely the large input of energy that allows for increasing efficiency of other inputs, including land and labor.

Plentiful modern energy fundamentally underpins decoupling.

Plentiful modern energy thus fundamentally underpins decoupling.[93] But the production of energy itself can also have important environmental consequences in the form of greenhouse gas emissions and conventional air pollution. This trade-off can only be mitigated by moving up the technology ladder for energy, toward less-polluting sources.

2.4 SUBSTITUTION: CASE STUDIES

MEAT

The domestication of animals for meat production takes pressure off wild animal populations. Humans in the late Pleistocene often relied heavily on wild meat for energy and protein.[102] A population of perhaps two million humans was estimated to have killed millions of large mammals annually during this period.[102] However, larger human populations, declining abundance or extinction of large herbivores, and deforestation driven by agricultural expansion led to diminishing wild meat harvests.[102,156] Starting around 11,000 years ago, a handful of mammals (including goats, sheep, pigs, and cattle) were domesticated for meat consumption, but more importantly for use as draft animals in agriculture and for transportation.[157] While meat consumption was low in early agricultural societies, and remained so almost all the way up to the Industrial Revolution, meat could now be obtained without killing wild animals.[102] Whereas unsustainable wild meat harvesting continues in many developing countries today, most of the developed world has almost entirely decoupled meat production from the killing of wild animals.

Although reducing pressure on wild animal populations, producing meat from domesticated animals also has environmental impacts, particularly in terms of land use. As much as three-quarters of all agricultural land today is dedicated to animal products, either for feed crops or pasture.[98] However, the harm to biodiversity from land use of farmed meat is arguably lower per unit of meat production than the enormous damage caused by wildlife hunting. Meat produced in The Netherlands requires from 7.7 m^2/kg for chicken to 29 m^2/kg for beef.[158] Replacing the five million tons of bushmeat harvested in Central Africa every year[43] would thus require on the order of 0.1% to 0.3% of the global farmland area.

The environmental impacts from meat production vary between systems. For example, in the United States, conventional feedlot systems have 45% lower land requirement, 51% lower nitrogen excretion, 51% lower phosphorous excretion, and 40% lower greenhouse gas emissions than grass-fed systems per unit of beef production.[159] These differences are accounted for by conventional systems' greater productivity, which reduces the maintenance cost (nutrients for vital functions and minimum activities) per unit of beef produced.[101]

WHALES

In the 19th century, whaling became a large, global industry with the potential to significantly reduce populations.[160] During this period, whales were hunted for three main economic goods: illumination, lubrication, and stiffener.[161] Illumination and lubrication were provided by oil from sperm whales (sperm oil) and from baleen whales (referred to as whale oil); stiffener came from the whalebone or baleen from baleen whales. After growing rapidly through the first half of the 19th century, whaling — measured in terms of number of voyages as well as the output of oil and other products — collapsed around the middle of the century and became marginal as early as the 1880s.[161,162]

The emergence of cheaper and better substitutes for whale oil in illumination explains the decline in whaling in the 19th century.

The 19th-century decline in whaling was primarily driven not by scarcity of whales, but by the emergence and eventual market dominance of substitutes.[161] During the period when whaling collapsed, the output of sperm and whale oil per voyage was stable — each whaling voyage returned with about as much whale and sperm oil in 1870 as it did in 1840.[162] The world was not running out of whales.[161] The price of sperm and whale oil — another indicator of scarcity — did not rise significantly during the decades when the whaling industry collapsed, suggesting that demand fell in tandem with supply over this period.[163] In fact, the second half of the 19th century saw a slow decline in the prices of sperm and whale oil — unthinkable if whale populations had been depleted in concurrence with stable or rising demand.[163]

Alternative illumination fuels gradually replaced whale oil. Competitive means of illumination had started appearing in the decades leading up to the middle of the 19th century.[161] Stearin candles, invented in the 1830s, outcompeted spermaceti in the candle market by the 1850s.[161] Lard oil burned in the so-called “solar lamp” (invented in 1841), camphene (appearing in the 1830s), coal gas (becoming competitive with sperm oil in the market for street lighting in the 1850s), and kerosene made from coal (starting in the 1850s) all chipped away at the market share of sperm and whale oil.[164] The final blow came in 1859, when vast reserves of petroleum, from which kerosene could be cheaply produced, were discovered.[164,165] Similarly, sperm and whale oil went from dominating the market for industrial lubricants in the 1850s to becoming marginal by the 1870s.[161] Finally, the market for baleen, which had held up quite well in the second half of the 19th century, collapsed after the invention of spring steel in 1908.[165]

AQUACULTURE

Aquaculture increasingly takes pressure off wild fish stocks as feed-to-meat conversion ratios improve and plant-based feeds substitute fish-based feeds.

Aquaculture can increasingly decouple fish production from wild fish stocks, thereby reducing humankind's impacts on marine biodiversity. Farming of herbivorous and omnivorous fish like carp and tilapia, whose feed is derived largely from terrestrial plants, is already almost entirely decoupled from wild fish stocks.[166] However, most carnivorous fish like salmon, as well as shrimp, continue to rely on proteins and lipids derived from wild fish, and therefore do not necessarily take pressure off wild fish stocks in the aggregate. Twenty years ago, it took on average a little over 1 ton of wild fish biomass to produce 1 ton of farmed fish biomass.[167] However, aquaculture has rapidly decoupled from wild fish since then: in 2007, it only took 0.63 tons of wild fish to generate one ton of farmed fish — an improvement by over 4% per year over the preceding decade.[167] In 1995, it took 7.5 tons of wild fish to produce 1 ton of salmon; eleven years later it only took 4.9.[168]

These improvements were due to three factors: an increasing share of omnivorous fish, higher feed conversion ratios (the amount of feed required to produce one unit of farmed fish), and substitution away from wild fish-based ingredients in fish feed.[167] Substitutes include terrestrial plant-based proteins and oils, oils produced by algae, animal by-products, and seafood by-products. The trend of decreasing proportions of fishmeal and fish oil from wild fish has been possible thanks to scientific advances in fish feeding, nutrition, and dietary manipulation, along with genetic modifications making farmed fish more tolerant of plant feedstuffs in their diet. Already, Atlantic salmon can tolerate up to 75% of oil and 50% of protein derived from plants, and these proportions are likely to continue increasing.[167]

Aquaculture, even if decoupled from wild fish, comes with its own set of problems. Plant-based feeds require land for their production, adding to the land footprint of food production (although fish require far less plant-based feed to produce protein than chicken, pork, or beef[169]). The establishment of fish farms can cause habitat loss as areas are cleared for pond construction.[170] Shrimp farming, in particular, has been a major driver of mangrove forest destruction.[166,171,172] These impacts can be mitigated by better location of fish and shrimp farms and the implementation of best practices; many forms of aquaculture today do not entail the loss of important wildlife habitats.[173] Aquaculture can also cause pollution in the form of nutrients and chemicals, leading to eutrophication, oxygen depletion, and other problems.[170] Pollution can be greatly mitigated through polyculture, where fish are co-farmed with seaweed, microalgae, or bivalve species like mussels or scallops, which reduce the nutrient load in the water.[173,174] It can also be reduced by the use of closed and semi-closed water systems that recycle the water with biological and other methods.[171,175]

The end goal is not complete decoupling of fish production from the oceans. When harvested at biologically sustainable levels, wild fish stocks can remain in good conservation status while providing food for humans without the land footprint or pollution associated with other protein sources. However, most wild fish stocks today are exploited at close to, or above, their maximum sustainable yield. Less than 10% of global fish stocks are fished at below their biologically sustainable level and thus have some potential for increased production; rebuilding overfished stocks could add about 20% to global wild fish production.[44] Aquaculture today supplies just over half of all fish for direct human consumption, having more than doubled its output between 2000 and 2012.[44,176] In coming decades, most additional demand for fish needs to be met from aquaculture in order to ensure healthy populations of wild fish.

FUELWOOD

Historically, the use of wood for fuel had devastating impacts on forests around the world. Wood harvesting for fuelwood or charcoal was a leading cause of deforestation and forest degradation for centuries leading up to the Industrial Revolution.[177–179] During this period, most fuelwood was for domestic consumption for heating and cooking.[178] Although human populations were far smaller than today, the very high levels of per-capita consumption made for very large impacts on landscapes in Europe and North America. In Central Europe in the

18th century, 30 m^3 of fuelwood consumption per household was a common — an order of magnitude higher than today's average European per-capita consumption of less than 1 m^3 for industrial roundwood and fuelwood together.[104,180] In the then-forest-rich United States, per-capita consumption of fuelwood peaked at over 16 m^3 per capita per year in the 1840s.[181] That is 14 times higher than the per-capita demand for wood for all uses in the United States today. Total fuelwood consumption in the United States peaked in the 1870s at 500 million m^3 per year — that is 40% higher than total wood consumption in the United States today.[104,181]

Forests are spared when humans move from reliance on fuelwood to modern fuels like natural gas, liquid petroleum gas, or electricity.

Wood also had several important industrial uses, particularly as a source of heat for the production of glass, salt, and iron.[177,180] In early modern England, producing 1 ton of wrought iron required about 50 m^3 of wood.[180] In 1820, charcoal production for the iron industry in Belgium required the annual yield of more than 50% of the country's total forest area; two decades later, the corresponding figure in France was 14%.[182] In the United States in 1840, wood corresponding to the annual yield of 2 million ha of forest was used for the same purpose.[182] Glass manufacturing in just one small region of Central Europe (Silesia) in the 18th century required an annual supply of wood corresponding to 1,000 ha of clear-cut forest or the sustainable yield of 100,000 ha.[180] A single salt works in the Tyrol, also in Central Europe, used the equivalent of the annual yield of a forested area of 200,000 ha in the early 16th century.[180]

Rampant deforestation and conversion of natural forest into plantations had devastating effects on forest biomes in Europe and North America. In the 18th and early 19th centuries, there was increasing talk of a "timber famine," and vanishing forests were a central concern for early conservationists like John Muir and Gifford Pinchot.[183] What eventually halted this trend, starting in the second half of the 19th century in the United States and earlier in the United Kingdom and Germany, was coal.[180,181] In the United States, wood went from providing 80% of energy in the 1860s to 20% in 1900 and as little as 7.5% in 1920.[184] Globally, biomass (chiefly from wood) went from providing nearly 100% of primary energy in 1850 to 50% in 1920 to around 10% in the last few decades.[185,186] The transition from wood to coal relieved European and North American forests of an enormous pressure and has been essential to the recovery over the 20th century of forest area in both regions.[107,187] In England as early as 1850, replacing coal with wood at the same level of energy consumption would have required an area one-and-a-half times the size of England and Wales.[188] With the per-capita fuelwood consumption of the United States in the mid-1800s but today's population, the United States would need more than 5 billion m^3 of wood, about 14 times the total roundwood production in the United States in 2012.[104,181]

Today's energy system is remarkably decoupled from land use. Fossil fuels, nuclear, and hydro, which together supply virtually all commercial energy today, use less than 0.2% of the world's ice-free land surface — 200 times less than pasture and cropland together.[67,189] Yet traditional biomass, including fuelwood and charcoal, continues to be widely used, especially in poor countries, supplying an estimated 6% of total primary energy (commercial and noncommercial) globally in 2012.[186] Traditional biomass accounts for 83% of residential energy use in Africa and 74% in Asia.[190] Per-capita consumption of fuelwood is not as high in the tropics today as it was in temperate Europe and North America in the 19th century. Average per-capita consumption is about 0.6 m^3 in Africa and 0.5 m^3 in South America today, though rates in specific locations can probably be considerably higher.[104] Yet the effects, in the form of deforestation and forest degradation, can still be very large when aggregated over large populations, as documented in Chapter 1.

FERTILIZER

The substitution of synthetic fertilizer for organic fertilizer may be the largest single contribution to lowering humanity's land footprint. Organic farming relies heavily on nutrient recycling, by applying crop residues, manure, compost, and sometimes human waste to the fields. However, this is far from a closed loop in modern societies. For practical, sanitary, economic, and other reasons, only a small portion of these materials can be returned to the fields, and because of leaching, volatilization, and other losses along the way, an even smaller fraction ever reaches and can be taken up by the crops.[191,192] Atmospheric deposition of nitrogen makes up for only a small part of the resultant nitrogen shortfall. The remainder of the shortfall can, in principle, only come from one source: nitrogen-fixing legumes.[191]

Fully organic systems may require twice as much land as systems using synthetic fertilizer to grow a given amount of food. Growing legumes for the purpose of adding nitrogen to the soil requires additional land, which is not accounted for by measuring the yields of a single field in a single harvest.[192,193] This has been called the "shadow land footprint" of organic farming. The magnitude of this shadow land footprint has not been determined with any precision. An extensive review comparing the ecological and agronomic implications of legume versus synthetic fertilizer sources of nitrogen takes as "typical" a ratio of 1 unit area legume to 1 unit area crop.[192] In other words, for every hectare of crop, a fully organic system requires another hectare of legumes. This ratio would increase if the yields of crops increase at a faster rate than the per-hectare rate of nitrogen fixation by legumes, which has very likely occurred over the past century, especially during the so-called Green Revolution.

Since few organic farms today set aside a hectare of legumes for every hectare of crops, they benefit from an external nitrogen subsidy, especially in the form of manure, that would not exist if all farming were organic.[194] The actual extra land required to supply nitrogen to organic farms — which currently make up less than 1% of agricultural land[193] — may therefore be limited in the present moment. The point, rather, is that without the invention of synthetic fertilizers, far more land — perhaps twice as much — would be needed to produce any given amount of food.

WOOD MATERIAL

The substitution of non-wood materials for wood is an important factor behind the relative decoupling of wood consumption from economic growth. In the 60 years between 1945 and 2005, world demand for materials overall (construction minerals, ores and industrial minerals, fossil energy carriers, and biomass) quintupled; demand for construction minerals went up by more than a factor of 10 and continues to rise.[19] Yet during the same period, demand for industrial roundwood, which is used as a construction material and for paper pulp, increased by less than a factor of three.[104,109] Since the mid-1980s, global demand for industrial roundwood has plateaued, and since 1960, per-capita consumption is down by more than a quarter.[104] In the United States, per-capita consumption of industrial roundwood is down by about two-thirds since the early 1900s.[184] Before the 20th century, wood was used for a vast array of purposes, including houses, ships, bridges, vehicles, and railroad ties.[177,195,196] While some of these uses remain to this day, wood has to a large degree been replaced by modern materials like steel and concrete,[196,197] which require far less land for their production, yet may entail larger life-cycle greenhouse gas emissions.[198]

RUBBER

Synthetic rubber, which has a very small land footprint, spares land by avoiding the conversion of natural habitats to natural rubber plantations. Natural rubber still accounts for about 40% of world rubber supply.[199] This is partly because of its superior qualities, but it is also a consequence of its relatively low price in relation to synthetic rubber, which is produced from petroleum. Had it not been for the synthetic substitute, natural rubber plantations would have to expand by another 10 to 15 million ha, likely in biodiversity-rich tropical countries, to meet global market demand.[68,200]

FIBER

The land footprint of plant-based fibers has declined, thanks in part to synthetic fiber substitutes. World demand for fiber increased by nearly 80% over just 18 years, from 1992 to 2010, yet the land footprint of plant-based fibers — principally cotton — declined by 9%.[201,202] This is in part because of steadily rising yields of plant-based fibers. Total production of plant-based fibers doubled between 1961 and 2013, yet the area harvested declined.[67] An equally important factor behind the lack of expansion in the area of fiber crops is substitution of synthetic for natural fibers.[197] Between 1992 and 2010, the share of synthetic fibers in world fiber production increased from 40% to 60%.[201] This includes the substitution of synthetic fibers for wool[203]: world output of wool from sheep and lamb declined by more than one-third between 1990 and 2013.[202] Synthetic fibers, like any substitute, come with their own set of environmental impacts, yet they are likely nature-saving overall. Meeting world demand for fiber with plant-based fibers would require on the order of 50 million ha more than today, equivalent to the area of Germany and England together.[67,201]

DRAFT ANIMALS

Moving from draft animals to mechanization significantly reduces the land footprint of agriculture. Draft animals used in farming require feed, whose production takes up large amounts of land. In the United States immediately preceding mechanization of agriculture, some 25 million farm horses and mules required a dedicated area of about 35 million ha for feed — about one quarter of the total farmland at the time and nearly equal to the size of California.[154] Replacing draft animals with tractors therefore cut the land footprint of US agriculture by 25% in a matter of a few decades. Today, hundreds of millions of animals, principally oxen, water buffalo, horses, mules, and cattle, are still used for mechanical power in farming in developing countries.[204] Their land footprint per head is likely not as large as for early 20th-century US horses, which amounted to 1.2 ha; draft animals in China in the early 1950s only required 0.13 ha per head.[154] Still, the total land required to feed today's draft animals may be in the millions of hectares — land that could be returned to nature if tractors replaced animals.

2.5 INTENSIFICATION

LAND SPARING AND THE BIODIVERSITY TRADE-OFF

Rising yields on existing farmland has allowed total crop production to go up more than threefold since 1961 while cropland area expanded only 13%.[67,202] This is an example of intensification, where more of the same good is produced on land already used. Other examples of intensification include rising yields in forestry, and urbanization, which increases the density of human settlements. Intensification allows demand to be met on a smaller area, thus sparing natural habitats from conversion to productive uses like farming, forestry, and settlement.

However, intensification also leads to biodiversity loss, as it tends to result in fewer species being able to persist on the fields, plantations, or built-up areas in question.[71,205] This has been the case, for example, in Europe, where populations of common farmland birds have declined over several decades.[206] The flipside of this is that maintaining high levels of biodiversity on farmland or in forestry — also known as a "land sharing" strategy — likely involves lower yields than would otherwise be possible, leading to expansion of farmland into natural habitats in order to meet demand.[71,207] Consequently, there is no free lunch for biodiversity when it comes to providing more food, timber, and housing.

Intensification allows demand to be met on a smaller area, thus sparing natural habitats from conversion to productive uses like farming, forestry, and settlement.

Global yield improvements lead to land sparing, but not always at a one-to-one ratio, especially in the short term.[208] Higher yields can lead to a rebound in food demand, stimulated by lower food prices.[135,209] But in the longer run, income growth likely overwhelms the effects of food prices, such that in countries past a certain income threshold, food demand is saturated and thus less responsive to prices.[90] Even accounting for short-run rebound, Thomas Hertel et al. estimate that the Green Revolution reduced land expansion by half compared to a counterfactual scenario without a Green Revolution — sparing an area larger than Western Europe.[135]

How to increase production of food, timber, and other goods while preserving as much biodiversity as possible at larger scales — ie, from the landscape to the global level[210] — depends on different species' habitat requirements. That is, it depends on which, and how many, species can persist in natural habitats, and on farmland or production forest with different levels of productivity.[71] Intensification is, broadly speaking, the best strategy in situations where there is a big difference in biodiversity between natural habitats and farmland (ie, where there is a big drop in biodiversity upon conversion from natural habitat to farmland), and where the rate of biodiversity loss in relation to yields is lower once the land has been converted.[71] A land-sharing strategy can be preferable when there is less difference in biodiversity between natural habitats and low-intensity farmland or forestry, and where intensification causes accelerating biodiversity loss.[71]

LAND SPARING IN THE TROPICS

The relative conservation values of natural habitats — primary or secondary — and farmland in tropical regions suggests that intensification is preferable from a conservation perspective.[210,211] In other words, the priority is to avoid further conversion of natural habitats. The tropics are particularly relevant in the context of agriculture and biodiversity, since that is where much agricultural expansion occurs today — mostly at the expense of forests. Between 1980 and 2000, for every 10 ha of agricultural expansion in the tropics, 5.5 ha of primary forest and 3 ha of secondary forests were lost.[212]

Many species in tropical regions are dependent on primary habitats — areas that have not been converted or heavily disturbed for several decades or centuries[213] — for their survival.[214] They are simply unable to maintain viable populations in secondary habitats, consisting of natural regrowth following abandonment or as part of shifting cultivation, or farmland. They may, however, be able to persist in forests that have been selectively logged.[215,216] These primary habitat specialists are often the most threatened species.[214] For these species, less primary habitat cannot be compensated by more secondary regrowth or farmland; the only way to conserve these species is by avoiding conversion of primary habitat in the first place.[217]

Secondary forests have greater biodiversity than farmland, but still less than primary forests or forests subject only to low-intensity, selective logging. In a review by Navjot Sodhi et al., the difference in "ecological health" — an index summarizing factors like species richness, species abundance, and ecosystem structure — was 60% larger between primary forest and farmland than it was between primary forest and disturbed forest, which includes secondary forest.[218] Mammals are relatively able to recolonize secondary forest, but even here, it may take decades if not centuries for mammal diversity and composition to approach that of primary forests.[219,220] Trees and other plants associated with primary forest are even less able to colonize secondary forests.[221] In a meta-analysis of 138 studies, Luke Gibson et al. found that secondary forests "invariably have much lower biodiversity values than do remnant areas of relatively undisturbed primary forest."[217]

In farmland even fewer of the primary forest specialists remain, and the species mix is often dominated by more widespread, generalist species.[71,207] Evidence suggests only around half of forest species are present even on extensive, wildlife-friendly farmland.[71,207] Even this may be an underestimation, due to extinction lags (forest species initially persisting on converted land but unable to maintain viable long-term populations), spillover from nearby primary forest, and shifting baselines (the reference forest having already lost some species because of disturbance).[207,214]

One way that farmland can retain biodiversity is through interspersed patches of natural habitat. However, a hectare of habitat isolated in the midst of farmland may not hold as much biodiversity as a hectare of habitat that is part of a larger area of contiguous natural habitat because species richness is often related to the size and connectivity of habitat patches, where larger size and greater connectivity means more species.[222,223] When David Edwards et al. compared patches of forest within oil palm plantations — promoted as a wildlife-friendly measure — to the neighboring unused forest, they found the abundance of priority bird species to be 60 times lower in the former.[224] At the landscape level, these species would have been much better off with homogeneous palm oil plantations that encroached less on the primary forest.

Empirical evidence in support of intensification in tropical regions includes a study by Ben Phalan et al., showing that land sparing consistently results in higher landscape-level biodiversity in sample regions in Ghana and India.[225] This finding was reinforced in a later modeling exercise, also by Ben Phalan et al., which concluded that "many more of the world's birds could be threatened by cropland expansion than by efforts to increase yields on arable land."[205] Similar results have been shown for lowland rainforests in Southeast Asia, where David Edwards et al. find that the abundance of birds, beetles, and ants was higher in a land-sparing scenario than in one with lower logging intensities over larger areas.[226]

LAND SPARING VERSUS SHARING OUTSIDE THE TROPICS

Intensification is likely to be preferable in many regions outside the tropics as well, especially in “frontier landscapes” with relatively short land-use histories.[210] For instance, Rebecca Tittler et al. find that concentrating logging operations in a smaller area, rather than spreading the impact more evenly across the landscape, favors biodiversity in Canada’s boreal forest.[227] There is also support for intensification in the context of urban development, where higher-density but less biodiverse urban space is associated with higher landscape-level biodiversity than low-density scenarios, especially under high levels of urbanization.[228,229]

The case for intensification is perhaps less clear cut for non-forest biomes, and for regions with longer histories of farming.[210] In the case of natural grassland versus pasture, for example, it is possible that light grazing of grasslands is compatible with high biodiversity and that most species are lost only at high densities of cattle[230] (although see Alkemade et al. 2012[231]). Here, extensification, with low stocking densities over larger areas, may be a winning strategy.[230] The same has been suggested for areas, particularly in parts of Europe, with long-standing traditional farming practices that maintain mid-succession habitats for many species.[207,210] Here, agricultural abandonment may in fact lead to a loss of threatened species,[232] at the same time as it creates opportunities for rewilding.[136]

A GLOBAL PERSPECTIVE

Improving agricultural productivity may enhance the competitiveness of a region’s farming products, thus incentivizing further expansion of farmland within that region.[209,233,234] This reality does not negate the global land-sparing benefits of intensification, but it does mean that the benefits may be experienced outside the region whose yields have improved.[135,235,236] For a region to reap the biodiversity benefits of intensification, effective policy and planning is required.[235,236] Over the past decades, some regions, like the US Midwest or more recently Brazil have taken on an ever-larger share of global food production, thereby reducing land-use pressures in the rest of the world.[237] This has been part of a broader pattern whereby farmland area is contracting in developed regions like Europe and North America while expanding in developing countries, especially in the tropics.[212] The net result of these trends is difficult to evaluate, as it depends on complex biodiversity trade-offs and subjective values over which landscapes have a higher conservation value.[238]

High-yield agricultural systems tend to have equal or lower environmental impacts — including water depletion, soil erosion, and pollution from fertilizers and greenhouse gases — per unit production than lower-yield systems.

Yet it is clear that in order to meet a projected doubling of global crop demand over the next few decades without losing a large amount of natural habitat, including tropical old-growth forests, intensification should be the priority across much of the world's existing farmland. The best candidates for such intensification are areas where farmland biodiversity is already low and intensification thus leads to proportionally less biodiversity loss.

INTENSIFICATION SIDE EFFECTS

High-yield agricultural systems tend to have equal or lower environmental impacts — including water depletion, soil erosion, and pollution from fertilizers and greenhouse gases — per unit production than lower-yield systems. This means that as more countries are able to meet their potential yields through adopting better technology, they are also likely to reduce their ratio of environmental impacts to production.

Rich countries, characterized by high-yield agricultural systems, have consistently higher nitrogen efficiency, which is defined as the proportion of external nitrogen inputs that is recovered in harvested products, than poorer countries with lower yields, implying less pollution per unit crop production in higher-yield systems.[239] Aggregate crop yields in OECD countries are 70% higher than in non-OECD countries, with only 54% greater nitrogen inputs.[239] Countries' nitrogen use efficiency typically declines at early stages of development — evident for instance in China today or the United States in the 1960s — but then starts improving after a certain point, reached by the United States and most European countries in the 1970s and 1980s.[239–241] The nitrogen surplus per hectare of farmland in OECD countries declined by more than a quarter between 1990 and 2009,[242] even as yields went up. The Netherlands today uses the same amount of fertilizer as it did in the 1960s but has double the crop yields.[241]

High-yield intensive farming systems are not inherently more damaging to soils than extensive low-yield systems. Four-fifths of all degraded farmland is located in the developing world regions of Africa, Asia, and Latin America; 60% is in dryland regions unfit for intensive agriculture.[243] Rates of soil loss have been estimated to be more than twice as high in developing countries than in developed countries.[244] Technologies for reducing erosion, including conservation and no-till methods, exist and have been increasingly adopted in North America and other regions.[243,245–247] In the United States, total erosion from cropland fell by 40% between 1982 and 1997[246] in spite of increasing yields and output.

In terms of greenhouse gas emissions, intensive systems tend to have higher emissions at the scale of the agricultural operation itself, in part accounted for by the fossil-fuel intensive production of synthetic fertilizers.[248] However, their higher yields means that less land needs to be converted to farming, often from carbon-dense ecosystems like forests.[248–251] Jennifer Burney et al. find that over the period 1961 to 2005, intensification reduced net greenhouse gas emissions by up to 161 gigatons of carbon compared to a non-intensification counterfactual.[248]

Given climatic and other geographical factors, it is hard to evaluate how water-use efficiency relates to crop yields. However, many of the technologies that can reduce water losses from irrigation, like drip irrigation, require capital investments that may only be feasible in more profitable, higher-yield agriculture.[252] A study by David Gustafson et al. shows consistently higher water-use efficiencies (cubic meters of irrigation water per unit crop output) in high-yield countries than in low-yield countries.[253] Aside from efficiency, agricultural water management needs to ensure that local water withdrawals do not exceed sustainable rates.

Organic farming tends to perform no better than its conventional counterparts in terms of pollution. A number of studies have shown that nitrate leaching in organic systems is comparable to or higher than in conventional systems, per unit crop output.[254–256] Similar patterns apply to emissions of ammonia and nitrous oxide.[256] By the most comprehensive review, organic farming across Europe was associated with around 50% higher nitrate leaching per unit output than conventional systems.[256]

3. LIMITATIONS OF EXISTING CONSERVATION TOOLS

3.1 PROTECTED AREAS

PROTECTED AREAS AS ACTIVE PROTECTION

Protected areas are the oldest and most common conservation strategy, covering over 15% of the world's land area outside Antarctica.[257] The parties to the Convention on Biological Diversity have pledged to increase this share to 17% by 2020.[137] Protected areas are intended to exclude some or all ecologically harmful human activities from an area by legal means. As such, they are a form of active protection, which seeks to overcome opportunity costs by legal, financial, or other methods. Active protection stands in contrast to passive protection, where land, animals, or other natural resources are conserved because exploiting them would not be economically rational.

This section reviews the potential of protected areas to achieve conservation. We find that protected areas, on their own, have a low capacity to overcome opportunity costs. When they do, ecologically harmful activities are typically displaced within nations or globally, rather than eliminated. This limits the potential of protected areas to contribute to large-scale conservation.

PASSIVE PROTECTION

Much, if not most, of the land under protected area status was already passively protected before receiving legal protection.[258] In these cases, the protected area only confirmed the baseline without making a difference to land use.[141] This is particularly the case in places at high elevation, on steep slopes, or at great distance from roads and cities.

For instance, fully three-quarters of the protected areas established in Latin America and the Caribbean through 2002 were outside places of high human impact.[259] Using a matching method — where areas under protection are compared with unprotected areas with similar characteristics — Kwaw Andam et al. show that only 7% to 9% of forests protected in Costa Rica between 1960 and 1996 would have been deforested in the absence of protection.[260] Similar patterns of low additionality were found in all 147 countries assessed by Lucas Joppa and Alexander Pfaff.[258]

PROTECTED AREA DOWNGRADING, DOWNSIZING, AND DEGAZETTEMENT

Governments often make protected areas weaker, make them smaller, or remove protection completely when opportunity costs emerge or grow after the protected area has been established.[261,262] This is known as Protected Area Downgrading, Downsizing, and Degazettement (PADDD).[261] For instance, Indonesia recently permitted the legal conversion of vast expanses of conservation and protection forests into production forests to allow open-pit mining and conversion to oil palm plantations.[261] Between 1981 and 2012 in Brazil, 5.2 million ha of parks and reserves were affected by downsizing or removal of protection.[263] This provides further evidence that protected areas are largely located where they do not conflict with other economic interests, that is, where opportunity costs are low or nonexistent.

Protected areas are largely located where they do not conflict with other economic interests, that is, where opportunity costs are low or nonexistent.

WEAK ENFORCEMENT

In other cases where protection competes with economic interests, protected areas are often weakly enforced. A review of over 4,000 sites found less than 25% to be under sound management; about 40% have "major deficiencies."[264] In South Asia (encompassing Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka), legal protection has had no effect whatsoever on the ground: Natalie Clark et al. find that habitat conversion rates inside protected areas is "indistinguishable from that on unprotected lands," and that habitat conversion rates do not decline following the establishment of a protected area.[265] There is uncertainty in how to understand weak enforcement. It could be interpreted as a simple lack of resources. It could also be interpreted as illustrating the limits to the opportunity costs that local and national communities are actually willing to accept. Tougher enforcement in the face of high opportunity costs may be politically or economically unfeasible.

ADDITIONALITY

All of the above examples — where protected areas are located in places under no threat; where protection is scaled back when an economic opportunity appears within the protected area; and where protected areas make no difference to the baseline through inadequate enforcement — illustrate the ways in which many protected areas do not actually overcome any opportunity cost. In other words, they do not represent additional conservation, in that they do not change land use or resource exploitation from the baseline. Many of the world's protected areas fall in one of these categories, showing that the willingness of societies to make economic sacrifices for the sake of nature conservation is in most cases very low.

Yet, some fraction of protected areas represent additionality; that is, they would have been converted or exploited in the absence of legal protection. However, in these cases, two further factors may undermine protected areas as a conservation strategy.

OPPORTUNITY COSTS: DO NO HARM

Protected areas that successfully limit ecologically harmful activities like deforestation and wildlife harvesting impose opportunity costs — such as the income foregone from hunting, farming, or fuelwood harvesting — on people locally and nationally.[266–268] In some cases, protected areas impose an additional cost in the form of crop damage or livestock predation by animals from within the protected areas.[269] These costs may or may not be offset by extra income resulting from ecotourism, research, infrastructure development, or other employment opportunities.[268,270]

The net impact of protected areas on poverty in affected communities depends on many local factors, including institutions and the design of the protected area intervention. There is good evidence that many protected areas, particularly in developing regions, have historically exacerbated poverty through displacement of communities and limitations on resource use.[271–275] There is also evidence of the opposite: protected areas in Costa Rica, Thailand, and Bolivia have been shown to alleviate poverty.[276,277]

The former situation, where protected areas exacerbate poverty, is inequitable and may infringe on human rights; as such, it is an unstable proposition.[266,278] This has been recognized by international organizations for more than three decades, and the "do no harm" principle was consolidated at the 2003 World Parks Congress.[267,268] Living up to this principle, through financial compensation, investments in ecotourism or infrastructure, or other means is entirely possible, but requires monetary and other resources. Alexander James et al. estimated that the annual opportunity cost of protected areas in developing countries around the year 2000 — based on the land price at fair market value — was as much as 15 times higher than the sum spent annually on these protected areas.[279] With finite conservation budgets, therefore, the do no harm principle may reduce the amount of land that can be protected.

LOCAL LEAKAGE

When legal protection successfully excludes harmful activities from an area, this gain can be offset if these activities are displaced, or leaked, to adjacent areas.[280] This is generally the case with settlement, as well as subsistence activities like fuelwood gathering or grazing.[281] Paulo Oliveira et al. provide one of few empirical estimates of local leakage as a result of protected area establishment.[282] By comparing rates of deforestation and forest disturbance inside and outside a protected area both before and after its establishment, they were able to disentangle the effect of the land-use restriction from the effect of leakage. Like many other studies, Oliveira et al. show that the land-use restrictions successfully reduced deforestation rates inside the protected area relative to their pre-establishment baseline. However, they also show that there was a dramatic increase in deforestation in the unrestricted landscapes surrounding the protected area, strongly indicating leakage. This displacement of activities from within the protected area to its surrounding areas might in fact accelerate the rate of habitat fragmentation, as it polarizes the level of human impacts across the landscape.[283–285]

NATIONAL AND INTERNATIONAL LEAKAGE

If the production foregone as a result of protection is geared toward national and international markets, as is the case with much modern farming and forestry, demand will be met by production elsewhere.[63,237,280,281,286–288] In a sample of seven developing countries that have seen reforestation within their national borders over the past five decades, additional global changes in land use embodied in their net wood trade offset 74% of their total reforestation.[286] Similarly for Europe and New England, both of which have undergone a so-called forest transition — where forest area has increased as land is taken out of agricultural production — this has gone hand in hand with increased agricultural production elsewhere.[63] More than four-fifths of lost timber supply from public forest conservation in the Pacific Northwest was offset by increased production elsewhere in the United States and Canada.[289]

This may lead to a net *loss* of biodiversity globally because of the prevalence in tropical countries of high levels of biodiversity, weak environmental protection, logging practices that cause high collateral damages, and lower crop yields.[63] This has led Mary Berlik et al. to argue that forest conservation in rich countries gives an “illusion of preservation” as ecological impacts are simply shifted to other regions.[290]

CONCLUSION

To be truly successful at a landscape to national level, protected areas must overcome many obstacles. To make a net difference, they must overcome real opportunity costs, that is, exclude harmful human activities that would have taken place in the absence of legal protection. This requires enforcement, and avoiding the scaling back of protection when an economic opportunity appears. When protected areas do make a difference to conservation within their borders, in order to be stable long-term propositions, they must also fairly compensate affected groups, and ensure that harmful activities are not displaced to adjacent areas. Overcoming all these obstacles is difficult and costly, but it is possible.[291] To the degree that they do, they form an important landscape-level conservation tool. We will discuss this in more detail in Chapter 4.

It is important to understand, however, that because of national and international leakage, it is primarily at the local to national level that protected areas can make a real difference. Hence, while protected areas are a legitimate and potentially successful means of conservation at the local or landscape level, they cannot scale up to net conservation at the global level. While displacement does not necessarily lead to a one-to-one loss of biodiversity elsewhere, the continuing demand for crops, livestock, timber, and other land-based commodities worldwide suggests that protected areas have very limited, if any, capacity to reduce net habitat loss globally.

3.2 CONSERVATION BY COMMERCIALIZATION

The shortcomings of protected areas motivated the search for a way for conservation to pay for itself. One response that became widespread in the 1980s and 1990s centered on the small-scale, sustainable exploitation of ecosystem goods like fuelwood, wild foods, and wild rubber, as well as low-intensity logging. The idea was that by recognizing the value of these forms of wildlife harvesting to the livelihoods of local populations, and fostering markets for these goods in order to generate additional cash income, the economic gain from a relatively intact ecosystem like a standing forest might rival that of alternative land uses like conversion to pasture or logging.[292] This would create an incentive for conservation and at the same time benefit local people, thus offsetting the opportunity cost of conservation.[293,294] This win-win proposition was embraced by conservation organizations around the world, often as part of so-called Integrated Conservation and Development Projects.[293]

However, this strategy, sometimes referred to as "conservation by commercialization" or "conservation by use" has in most cases failed to deliver on its win-win promise.[293,295] The main reason for this is that the incomes from harvesting non-timber forest products like wild foods and rubber are very low. These ecosystem goods can supplement the livelihoods of the poorest and provide a last resort when other sources of subsistence or income fail to materialize.[296–299] They are not, however, a viable way out of poverty, since they are typically too slow growing and dispersed to yield any substantial surplus over the time and effort invested.[300–304] Dependence on wildlife harvesting is a symptom of poverty, not a way out of it.[305]

A number of studies have found that the per-hectare net value of wildlife harvesting or low-intensity logging cannot compete with the potential incomes from conversion to farmland or production forest.[306,307] In cases where conversion is an option and a threat, conservation is for the most part not the highest economic use of land.

Even relatively low rates of wildlife harvesting cause some level of biodiversity loss, as discussed in Chapter 1.[308,309] To increase profitability, more intensive management and cultivation is necessary, but this often leads to more severe impacts on forest ecosystems, lowering their conservation value.[301,302,310,311] Thus, based on an extensive review of case studies from Asia, Africa, and Latin America, Koen Kusters et al. conclude that trade in non-timber forest products is "not likely to reconcile development and conservation of natural forest."[300]

3.3 REGULATING ECOSYSTEM SERVICES

THE PREMISE

Regulating ecosystem services differ from provisioning ecosystem services in that they are not harvested but rather generate a flow of material services like water purification, air purification, water flow regulation and flood control, climate stabilization (through carbon sequestration and alteration of albedo and other characteristics of the earth's surface), erosion control, pollination, and pest control.[312] Using or benefitting from regulating ecosystem services does not harm nature in itself, and therefore, substitution of technology for regulating ecosystem services does not automatically save nature, as with provisioning ecosystem services.

The basic idea behind regulating ecosystem services as a conservation strategy is similar to that of conservation by commercialization: making conservation the highest economic use of land. This would be the case in situations where the net value of regulating ecosystem services provided by a given hectare of land, with disservices and transaction costs discounted, exceeds the value of an alternative land use like industrial farming, plantations, or housing development.[134,313] In other words, the benefit stream from the natural habitat must be greater than the benefit stream from the alternative land use. When this holds, and institutions exist to capture these values, conservation could result from the rational self-interest of actors like farmers, watershed managers, or public health agencies.[314,315]

For the strategy of conservation through regulating ecosystem services to work, the material value of the regulating service must be detectable and amenable to at least a rough estimation. Otherwise, no rational economic actor would be willing to pay for the purported benefits of regulating ecosystem services. If downstream water users pay for upstream conservation, it is because they have some evidence that it is a good economic decision. If farmers forsake production on part of their land to provide pollination services, it is because they think they would make more profit across all their land by doing so.

Of course, people may pay for or support conservation for any number of reasons, including aesthetic and moral, without any estimate of material value. But that is no different from ordinary conservation. By contrast, the premise of the ecosystem services framework is that it speaks to the material self-interest of economic actors. Without doing so, it cannot scale beyond the current confines of conservation to really affect large-scale land use and resource exploitation decisions.

Regulating ecosystem services make many important contributions to material human welfare through, for example, their role in food production, pollution reduction, flood protection, and carbon sequestration.[312] They can probably justify conservation in some local instances, as with buffer strips mitigating nutrient leaching from farmland, and mangrove forests providing coastal flood control.[316,317] Yet this does not necessarily mean that valuing them can make a large-scale difference to habitat and biodiversity loss. Several factors limit the viability and scalability of regulating ecosystem services as a conservation tool.

MANY REGULATING ECOSYSTEM SERVICES CAN BE PERFORMED BY SIMPLE ECOSYSTEMS

Protecting regulating ecosystem services does not necessarily result in the protection of those species, ecosystems, and places most valued by conservationists. For the most part, regulating ecosystem services can be provided by ecosystems far simpler than those typically targeted by conservation.[318] Most of the ecological functions underpinning regulating ecosystem services are performed by functional groups of species that are resilient or substitutable.[318] Primary, undisturbed habitats are generally no better at turning over matter and energy than habitats with a large share of introduced species.[319,320]

Protecting regulating ecosystem services does not necessarily result in the protection of those species, ecosystems, and places most valued by conservationists.

Looking at specific sectors, ecosystem services enjoyed by modern agriculture can be performed by a combination of invertebrates for soil structure, microorganisms for nutrient cycling, and vegetation cover for water provision and purification.[145,321] Carbon sequestration can be performed by homogeneous stands of eucalyptus or any other fast-growing tree. Erosion prevention and regulation of water flows can be performed by almost any set of plants and trees, as long as they provide an adequate amount of ground cover.[318] Air quality regulation is done by virtually any photosynthesizing plant or tree.

Loss of biodiversity within a given ecosystem may reduce the flow of regulating ecosystem services.[322] This is the case with carbon sequestration and soil organic matter creation, among others.[322] However, the empirical results are mixed when it comes to carbon storage, pest control, and pollination.[322] The evidence suggests biodiversity has no impact on freshwater purification, and there is not enough evidence yet to support a link between biodiversity and flood regulation.[322] However, these marginal effects, where they exist, must be put in the context of the difference in regulating ecosystem service provision between different ecosystems, and between natural habitats and land that has been converted to agriculture or other direct uses. What is more, in a majority of local ecosystems, species introductions offset extirpations, such that overall local species richness has stayed the same or gone up.[323–325]

From the perspective of simply providing regulating ecosystem services to humans, a far less diverse, more homogeneous, and less beautiful biosphere would in all likelihood work as well as a more diverse and beautiful biosphere. Those species and habitats most valued by conservationists for their aesthetic, intrinsic, or spiritual value are, as David Ehrenfeld has pointed out, "the ones least likely to be missed by the biosphere. Many of these [rare] species were never common or ecologically influential; by no stretch of the imagination can we make them out to be vital cogs in the ecological machine."[326] High levels of material human welfare are likely to be achievable without the remaining megafauna such as elephants and tigers, without unique habitats like the South African fynbos, without the spectacular landscapes of Yellowstone or Yosemite, and without most of the bird species that fascinate and delight people across the world.

MANY REGULATING ECOSYSTEM SERVICES CAN BE SUBSTITUTED

What is more, most regulating ecosystem services can be substituted or otherwise made redundant with technology. Air filters can capture pollutants from the atmosphere instead of trees. Better still, less-polluting technologies can replace more-polluting ones, negating the need for post-tailpipe pollution capture. Water treatment plants can capture water pollutants instead of aquatic ecosystems;[327] a combination of desalination and water treatment plants can allow cities to close the water cycle altogether, eliminating the need for any regulating ecosystem services. Pests can be tackled with pesticides rather than with biological control.[327] Pollination can be done by imported bees housed in trailers, rather than by native bees living in natural forests.[328]

Photosynthesis appears to be the only regulating ecosystem service that cannot yet be artificially replaced.[147] But even here, photosynthesis does not depend on the protection of natural habitats. Food can be grown hydroponically, indoors, with artificial lighting. Already, much industrial food production, from Iowa's cornfields to Brazil's soy farms, takes place in heavily modified environments far removed from any natural ecosystems.

REGULATING ECOSYSTEM SERVICES AND THE HIGHEST USE OF LAND

The fact that regulating ecosystem services can be substituted or performed by simple ecosystems does not mean they can never provide an economic basis for conservation. However, at the local and regional scale, several considerations apply.

For regulating ecosystem functions to have any value at all — to be a "service" — they must have a human beneficiary.[329] Ecosystems located remotely from economic activities like farming or forestry, or from human settlements, may not supply regulating ecosystem services of any value. This excludes many areas of high biodiversity value from the regulating ecosystem service rationale for conservation. However, ecosystems in such remote locations are often not threatened by conversion in the first place.[258] In these cases, conservation is already the highest use of the land, regardless of any regulating ecosystem services.

One exception to the geographical condition is carbon storage and sequestration, which affects the global climate regardless of where on earth it takes place. But the characteristics of climate change make any estimation of the value of carbon sequestration highly tenuous; the institutional challenges in implementing a global mechanism to capture this value are enormous; and leakage could cancel out any global benefits.[289,330–332]

For all other regulating ecosystem services, the site of production (ie, the natural habitat where the service is generated) and the site of consumption (eg, the cropland that benefits from pollination or cities benefitting from cleaner water) must be within a certain proximity, which depends on the specific service in question.[333] For pollination, it is a matter of hundreds of meters.[334] Air purification by plants is also highly localized.[335] The benefits of water purification and flow regulation can extend over an entire river basin.

Where the sites of service production and consumption are close, the value of the regulating ecosystem service is often correspondingly higher. But in the proximity of agriculture, farming, or settlements, the opportunity costs are typically also higher. At these scales, a paradox in the economics of regulating ecosystem services appears, as described by David Simpson.[333] If the regulating ecosystem service is produced diffusely — if it takes a lot of land to produce a certain amount of the service — then the per-hectare value of that service will be correspondingly low, and conservation will fail to compete on an economic basis with alternative land uses. If, on the other hand, the service can be performed very efficiently in terms of land, then the per-hectare value might be able to match that of the opportunity cost, but only a small area of conservation would be needed to provide an adequate amount of services.[333]

> There is little robust empirical evidence of cases where the value of regulating ecosystem services exceeds that of the opportunity cost of conservation.

As such, highly efficient regulating ecosystem services are self-limiting in terms of how much land they can conserve. This is probably the case with the instances where regulating ecosystem services are able to justify conservation, like buffer strips.[317,333] If a ten-meter buffer strip can absorb most of the nitrogen leaching from nearby fields, then the eleventh meter will not make much of a difference, and is therefore of low value.

The large literature on ecosystem services provides little robust empirical evidence of cases where the value of regulating ecosystem services exceeds that of the opportunity cost of conservation.[138,313,316] As such, the hypothesis that regulating ecosystem services can widely compete with alternative land uses has not been convincingly proven.[333] There are cases where, from a theoretical perspective, regulating ecosystem services are unlikely to outcompete alternative land uses. For example, it is implausible that the per-hectare value of services like pollination from natural forests can match the per-hectare profits from converting and farming that land.[313,328,336]

CONCLUSION

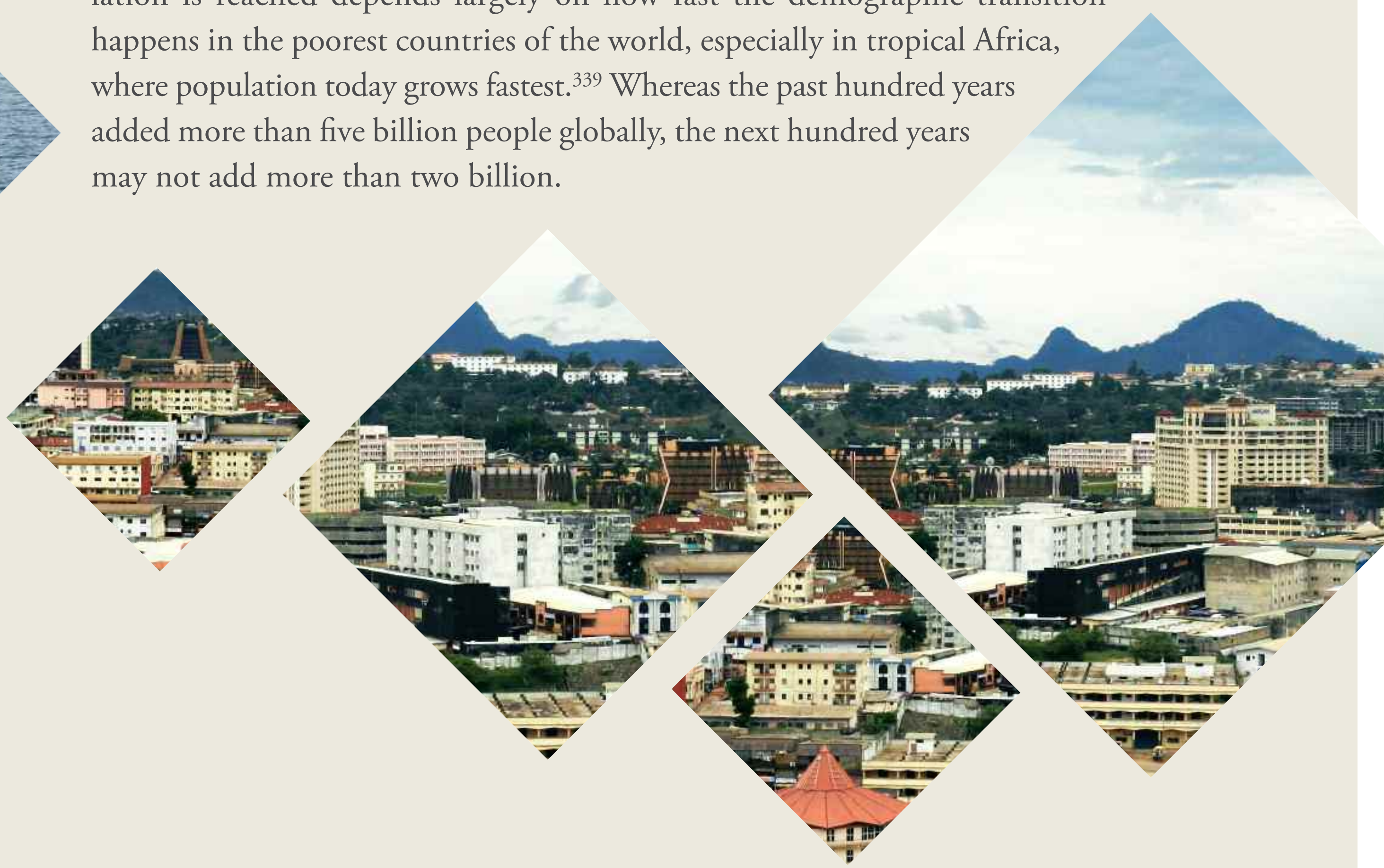
In sum, while the value of regulating ecosystem services can probably make conservation the highest use of land in some cases, the amount of land that can be saved this way is probably constrained by the self-limiting nature of highly efficient regulating ecosystem services.[333] And in cases where regulating ecosystem services really do outcompete alternative land uses like farming or logging, these activities are likely displaced rather than eliminated.[337] Just like in the case of protected areas, therefore, local gains thus do not automatically scale up to make a significant difference to global trends in habitat and biodiversity loss.

4. TOWARD A NEW FRAMEWORK FOR CONSERVATION

4.1 PEAK IMPACT IN THE 21ST CENTURY

Ongoing trends in population, consumption, and the technology factor make it possible that human impacts on the environment peak and decline this century. Peak impact is not inevitable but rather depends on concerted action by governments, NGOs, and private actors. As such, peak impact offers a concrete goal and an affirmative vision for conservation in the 21st century.

The goal of peak impact will be aided by the peaking and decline of the human population. The global population has been forecast to reach nine billion by 2070 and decline thereafter,[338] while other projections have it increasing further into the second half of the 21st century.[339] Exactly when and at what level peak population is reached depends largely on how fast the demographic transition happens in the poorest countries of the world, especially in tropical Africa, where population today grows fastest.[339] Whereas the past hundred years added more than five billion people globally, the next hundred years may not add more than two billion.



As more and more countries reach high-income status, the growth in demand for most material goods — and therefore natural resources — will eventually slow down at a global scale. Even so, the world will need to produce much more over the next few decades as poorer countries emerge from poverty and move toward higher living standards. Global demand for crops is forecast to double by 2050[148] and global demand for energy to rise by half by 2040.[186] Global energy supply would have to more than double for everyone to enjoy the current per-capita energy consumption of a developed country like Germany.[126,338]

Human impacts on the environment may peak and decline this century.

Trends in population and consumption combine into continued, but slower, growth in total consumption over this century. What will ultimately determine when and at what level peak impact occurs is the technology factor. There is scope for enough improvement in the technology factor to reach peak impact. For example, global yields of most major crops could be increased by up to 70% if all countries could match the best performers in their region.[340] If all countries met their potential for cropping frequency, annual crop production per unit land could be boosted by another 50%.[99] Carbon emissions from energy production would be 60% lower if all countries had the carbon intensity (CO_2 per unit energy) of Sweden.[126]

The arrival of peak impact — or, as Jesse Ausubel called it, the Great Reversal[169] — would constitute a turning point in the Anthropocene, the epoch during which humans have strongly shaped the global environment. After growing for centuries, the area of farmland would peak and decline, leaving behind an expanding space for nature. Less forest would be logged and waterways less polluted with fertilizers. The loss of habitat and biodiversity could be reversed. These reversals, if realized, could not only spare remaining natural habitats, but also open up new opportunities including ecosystem restoration and rewilding.

4.2 LIMITATIONS OF DECOUPLING AND THE NEED FOR A LARGER FRAMEWORK

Decoupling has the potential to significantly reduce aggregate human impacts on the environment. As such, it is a fundamental precondition for saving nature at large scale. But decoupling does not solve every conservation problem, and comes with its own limitations.

Decoupling does not guarantee that the landscapes conservationists care about most, such as old-growth forests, will be preserved, nor that land that remains in production will be concentrated in areas where ecological impacts are least significant. The geographical distribution of farmland and forestry could continue to shift globally, thus encroaching further onto primary habitat or other areas of high conservation value even as the total production area declines. The same concentration of agriculture in the most productive areas that is currently contributing to a global decoupling of farmland area from food production is also causing the loss of invaluable tropical rainforest in South America and Southeast Asia.[236,341]

> Decoupling does not solve every conservation problem, and comes with its own limitations.

Even with accelerated decoupling, some forms of environmental impact may continue growing for several more decades. More-efficient production processes may result in cheaper goods and services, resulting in a rebound in demand, until such time as demand is saturated. Even after peaking, large-scale impacts will persist through the century. For instance, even if total cropland area starts to decline within the next few decades, it will still necessarily cover a huge portion of ice-free land. Human extraction of freshwater, even if declining, will still leave less water for freshwater ecosystems.

Decoupling can also be inadequate in cases where environmental harm is not directly linked to the production of an economic good, such as with harmful species introductions.

Decoupling should therefore be understood not as an alternative to existing conservation strategies but an augmentation and a larger framework within which conservation efforts must situate themselves. Passive protection through decoupling and active protection through protected areas and ecosystem services are *both* required in order to achieve 21st-century conservation goals. Passive protection addresses the limited capacity of active protection to achieve aggregate reductions in human pressures. Active protection, within a framework of strategic landscape planning, addresses the limited capacity of passive protection to achieve optimal outcomes at the species or landscape level.

Below, we outline the contours of a broader strategy for conservation. We describe how ongoing decoupling processes can be actively accelerated, and how this relates to broader socioeconomic changes. We also explain how proactive landscape planning, including active protection in the form of protected areas and ecosystem services, can ensure better outcomes at the landscape level. Finally, we outline how innovation on the technological frontier pushes the long-term envelope of possibility for conservation. We can, however, only scratch the surface of possibilities that arise from this framework. Our hope is that conservation researchers and practitioners will fill in the many gaps and provide more case studies over months and years to come.

4.3 ACCELERATING DECOUPLING

ACTIVE DECOUPLING

Conservation organizations, government agencies, and private firms can contribute to accelerating the decoupling trends that are moving the world toward peak impact. While decoupling manifests as aggregate trends at the global level — for example in terms of the land area under agriculture — these emergent patterns stem from active, willed decisions, interventions, and policies at the local to national level. Spontaneous, organic market forces are very important but explain only a part of the ongoing decoupling processes. In other words, decoupling is as much a bottom-up process as is active protection. This is a framework for "active decoupling" as well as active protection.

SPREADING LOW-IMPACT TECHNOLOGIES

Continued and accelerated agricultural intensification could result in the land footprint of food production peaking and declining this century. This will require low-yield farming to be intensified or in some cases abandoned. Achieving high-yield agriculture requires the diffusion of not one but rather a cluster of interrelated technologies including synthetic fertilizers, pesticides, tractors, irrigation, and new seed varieties, as well as markets and infrastructure like roads, and refrigeration. Technological change through more precise and efficient farming practices can also reduce water consumption and nutrient pollution from agriculture.[342]

The conservation benefits from intensified agriculture can be very large. Ricardo Grau and Mitchell Aide document one case in Northern Argentina where the amount of protein produced on 4.7 million ha of traditional grazing could be supplied using just 16,000 ha of soybean farming — a reduction in land footprint of 99.7%.[343] The most productive livestock system in sub-Saharan Africa requires more than 20 times more land to produce a kilogram of protein than the most productive North American system.[344] Modern farming with multiple harvests per year replacing shifting cultivation can lower the land clearing required to produce a given amount of crops by over one order of magnitude.[345]

Substitution can bring conservation benefits in developing and developed countries alike. Defaunation of tropical forests can be reduced if more people got their protein from farmed animals instead of bushmeat. Forest degradation can decrease if more people moved away from fuelwood and toward modern forms of energy like liquid petroleum gas and electricity. Carbon emissions from energy can be reduced by moving away from fossil fuels and toward low-carbon energy sources like solar, wind, hydro, and nuclear. Wild fish can be spared through broader adoption of aquaculture. Dense cities can reduce the land footprint of human settlements. Desalination can take pressure off freshwater ecosystems.

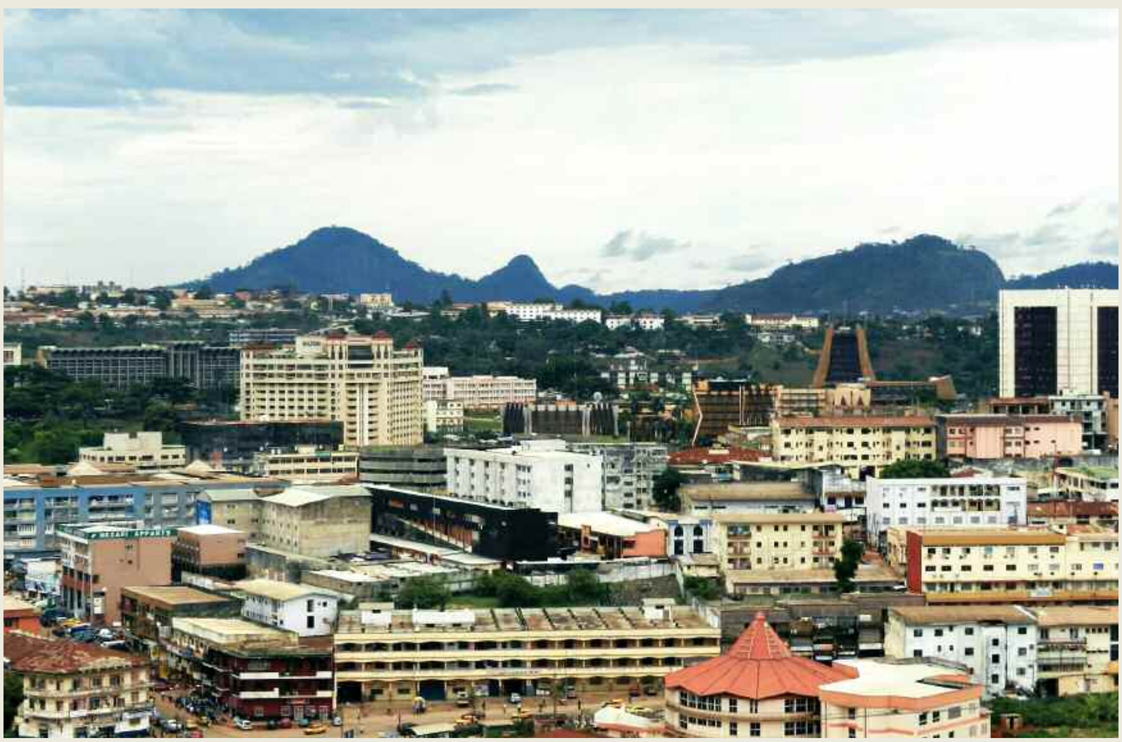
There are concrete on-the-ground substitution and intensification projects that governments, conservation organizations, and companies are already implementing. For instance, a program giving farming households subsidized coupons for fertilizers and improved corn seeds contributed to significant corn yield improvements in the mid-2000s in Malawi.[346] A similar program a decade earlier had positive effects on crop yields and was shown to have reduced forest degradation and led to intensification of existing farmland rather than area expansion.[347]

In India, the introduction of liquid petroleum gas has been tied to forest conservation and regrowth. Sunil Nautiyal and Harald Kaechele describe how, over two decades, a government program to increase the uptake of modern fuels in a number of villages in the Indian Himalayas nearly eliminated the use of fuelwood, leading to ecosystem recovery in this threatened biodiversity hotspot.[348]

Conservation organizations can also help ensure that decoupling trends are not reversed. For instance, in recent decades, biofuels from crops like corn, soy, and sugarcane has come to be used as a substitute for petroleum in liquid transportation fuels. Even the most land-efficient source of biofuels, sugarcane, requires more than six times more land to produce a given amount of energy than petroleum, and the least efficient one, soybean, requires about 20 times more.[349] Since biofuels derived from crops like corn or sugarcane cause direct or indirect land-use change, with associated releases of carbon dioxide and methane, their life-cycle carbon emissions may not be lower than those of fossil fuels.[350–355] Most current biofuels run counter to decoupling. So do some forms of organic farming, because of lower yields,[356,357] especially if adopted at larger scale or applied to bulk crops like cereals. Conservation-by-use programs tying local people's incomes to non-timber forest products like bushmeat or fuelwood harvesting may only delay the adoption of less environmentally impactful livelihoods.[298,358]

SUPPORTING MODERNIZATION

The intensification and substitution processes described above occur in a context of socioeconomic change, broadly referred to as modernization. Urbanization, income and consumption growth, and a shift from subsistence farming to manufacturing and services all underpin decoupling. These processes are in turn enabled by strong institutions, especially a strong state.



Urbanization, income and consumption growth, and a shift from subsistence farming to manufacturing and services all underpin decoupling.

Urbanization and agricultural intensification go hand in hand. As agricultural productivity rises nationally and internationally, the labor requirement tends to go down, as do food prices. At the same time, marginal agriculture becomes less and less competitive.[133,358] Together with increasing opportunities for off-farm employment, these processes can create a combined push and pull on people, away from unproductive, small-scale farming — which is often completely abandoned — and toward manufacturing or services jobs in cities.[133,359,360] This goes hand in hand with further consolidation and productivity improvements on remaining farmland.

Once in cities, people tend to buy food that comes from commercial farming systems with yields several times higher than in subsistence farming.[360] These productivity improvements tend to more than compensate for the increased per-capita food consumption — with increased overall calorie consumption and more protein-rich foods — that results from higher incomes, such that the per-capita land requirement can decline.[97]

Subsistence farming is not the only ecologically degrading activity abandoned when people move to the city. Bushmeat hunting, extensive grazing, wild foods gathering, and fuelwood collection are also largely substituted by lower-footprint sources of material sustenance. While the drivers of wild meat hunting and consumption are complex, evidence from many regions suggests that the relative price of substitute sources of protein — especially domestic livestock, chicken, and fish — together with the opportunity cost of hunting are key factors.[41,298,361–365] The highest consumption of bushmeat is found among the rural poor close to wildlife populations, where the cost of bushmeat is low and domestic farmed meat is unaffordable. As incomes rise, consumption of both farmed and wild meat can rise initially, but after some threshold when farmed meat becomes cheaper than wild meat, consumption of wild meat tends to decline toward zero. Broad and sustained modernization, therefore, appears to be a long-term solution to the bushmeat problem.

Urbanization and income growth is also closely linked to people climbing the energy ladder.[366] It is far cheaper to provide electric grid access in cities than in the countryside.[367] As a result, most progress on energy access in recent decades has occurred in cities. In Africa between 1990 and 2010, twice as many people got access to electricity in cities as in rural areas.[368] Even so, urbanization alone is often not enough. Many poor cities in sub-Saharan Africa, for instance, rely on charcoal rather than modern forms of energy, with considerable impacts on forests.[369] Income growth and public and private investments in energy infrastructure are therefore required in order for large numbers of people to climb the energy ladder and thus reduce pressure on forests.

Finally, fertility rates tend to fall as people move to cities, increase their incomes, and acquire education.[370,371] Modernization and economic growth enables producers in agriculture, forestry, and other sectors to adopt better, more environmentally efficient technologies that are often capital intensive.[372,373] And higher quality of governance means protected areas and other forms of active conservation can be better enforced.[235,374]

4.4 LANDSCAPE PLANNING

Decoupling through technological and socioeconomic change, as noted above, defines the boundary conditions for conservation — how much land and wildlife is left after human material needs have been met. In this sense, reducing the amount of environmental impacts per unit of goods and services is the first priority. When it comes to energy choices, sources with lower land requirements and carbon emissions should, where possible, be chosen over those with larger impacts. The same goes for agriculture, forestry, and other sectors: every opportunity for substitution and intensification should be identified and acted upon to the largest feasible degree.

Yet even with accelerated decoupling, food will need to be grown somewhere, metals will need to be mined, roads built, and dams constructed. Conservation stands a better chance of mitigating the impacts of these activities if it engages pragmatically with these economic activities and their stakeholders at a strategic landscape level, rather than opposing any development in an ad hoc manner.[375,376]

This pragmatic approach has two sides: locating production and locating protection. Conservation organizations have a lot of expertise in the latter, including biogeography, ecological processes, population viability, and landscape connectivity. The goal of this systematic conservation planning is to identify a portfolio of priority areas across a landscape that as much as possible captures the most unique elements of biodiversity, allows for the persistence of viable populations of target species, and allows for resilience in the face of climate change and other disturbances.[377]

To achieve these targets, conservation can draw on its existing toolbox, including protected areas, direct payments, and conservation concessions. As noted previously, these tools are not made obsolete by decoupling, but rather complement it. At the same time, active protection is made possible by decoupling, which lowers the opportunity cost of conservation.

As decoupling continues, more and more opportunities emerge for conservation. Agriculture will be abandoned in marginal areas. The number of people residing in rural areas worldwide is peaking, and is forecast to decline by at least 500 million by 2050.[378] Rural depopulation can open up new spaces for nature. These processes are already ongoing in many parts of the world. Agriculture is receding in Europe and parts of North and South America.[212,379] Wildlife populations are rebounding where habitats are expanding and hunting pressure is reduced.[380]

Yet these processes do not automatically lead to conservation. Lower land prices might be seized upon by urban sprawl. In many tropical regions, rural depopulation does not translate directly into forest regrowth, as even more extensive practices like pasture, which have lower labor requirements, take the place of croplands.[381]

There are good examples of how conservationists have taken advantage of decoupling for rewilding, regrowth, and restoration. The reintroduction of bison to large swathes of land in Montana and neighboring states is facilitated by low land prices and rural depopulation.[382] These, in turn, are related to shifts in national and global markets for agricultural products. One of the largest floodplain restoration projects in the Mississippi River basin, that of the Ouachita River in Louisiana, was made possible when farming in the area became an uneconomic proposition, resulting in very low land prices, which the US Fish and Wildlife Service and The Nature Conservancy seized upon.[383]

Conservation faces a different set of challenges where economic activities are expanding. Where roads, dams, and mines need to be constructed, the goal is to design and locate these in the least ecologically harmful way possible. This requires a proactive approach by conservation organizations.

One example of this is in evidence in the Mekong River in Southeast Asia. Here, a suite of hydropower dams, with a target for total generation capacity, is slated for construction with the objective of providing clean energy and a source of export revenue. Since these dams are likely to cause damage to biodiversity — especially the fish populations — in the Mekong and its tributaries, Guy Ziv et al. used a model to find the dam locations that would cause the smallest migratory fish reductions for any given energy requirement.[384] They found that for a given level of generation capacity, the impact on fish biomass from using one set of locations can be several times higher than with another set of locations. By choosing locations wisely, then, multiple objectives can be optimized so as to result in the smallest trade-off possible, or at least avoid the developments pathways with the highest biodiversity costs for any given level of generation capacity.

On the ground, decoupling and landscape planning often blend together. A single project may steer people's resource use away from a biologically rich area while at the same time allowing them to increase their crop yields or gain off-farm employment. Direct payments conditional on the non-degradation of a forest can give people the financial means of moving from fuelwood collection to electrical grid access, thereby doubly achieving forest protection. Conservation organizations can help identify areas where agricultural intensification would lead to the least damage to biodiversity, and then work with local and national governments as well as corporations to invest in infrastructure, financial support, and regulation that "crowds in" agricultural production in the target region, while establishing protected areas on land with higher conservation value.

Conservation organizations may promote the construction of hydroelectric dams or oil refineries to substitute electricity or liquefied petroleum gas (LPG) for fuelwood and charcoal while also working to situate the dams and refineries in the least damaging location possible. Similarly, road construction can be a precondition for agricultural intensification in target regions, but at the same time needs to be designed and located in the landscape so as to minimize harm to species and habitats.[385] Working with agricultural intensification, energy access, and other elements of decoupling thus becomes inseparable from a broader strategy for landscape planning.

4.5 INNOVATION ON THE TECHNOLOGICAL FRONTIER

Increasing adoption of existing low-impact technologies, along with landscape-level planning, can go a long way toward peak impact and local conservation success. But in the longer run, the envelope of technological possibility, and thus ultimately of global conservation, is pushed forward by innovation, radical and incremental. Examples of radical innovation include new seed varieties that enable higher crop yields, synthetic fertilizer that cuts the land requirement of food production by up to half, and nuclear power that provides low-carbon baseload electricity. New seed varieties alone are estimated to have spared 18 to 27 million ha since 1965, corresponding to a land area up to twice the size of England.[386]

Over the last two centuries, societies have transitioned in their energy production from biomass to coal to natural gas and petroleum to nuclear, wind, and solar power, reducing the carbon intensity of energy along the way.[387] Transport systems have evolved from horse and buggy to canals to railroads to automobiles and aviation. "Technological change," write Dominique Foray and Arnulf Grübler, "could offer reductions in the resource, materials, and environmental intensiveness of industrial societies that are not only marginal, but rather are by orders of magnitude."[388] As technological systems are reinvented in the 21st century, there is every chance of substantially reducing the human footprint on the environment in the process.

In the longer run, the envelope of technological possibility, and ultimately of global conservation, is pushed forward by innovation.

Markets are important drivers of innovation, yet the historical record shows that many important technologies trace their origins back to non-market environments, such as government agencies,[389] monopolies[390] (which are shielded from market competition), and universities.[391,392] In these conditions, innovation is not diffuse and organic, as in competitive markets, but rather willed, mission-oriented, and often involving collective action toward public goods. The upshot of this historical insight is that further acceleration of decoupling trends can be achieved by concrete action on the part of conservation organizations, government agencies, and other actors.

Research and development underpinning radical innovations, in particular, are more likely to take place outside competitive markets since it is often uncertain, expensive, and time-consuming.[393] For instance, many of the information and communications technologies that have become so central to today's economies were developed over many decades in government labs and agencies, or in public-private partnerships — often driven by the decidedly non-market imperative of national security.[394] The rapid and widespread changes in farming technology known as the Green Revolution had their origins in a set of particular technologies developed in a philanthropic setting, and their subsequent diffusion across the globe was driven in part by political and humanitarian concerns.[395] Still today, a majority of global investment in agricultural innovation comes from the public sector.[396]

More practically, there are several ways in which conservation organizations can engage with innovation. They can advocate for and support targeted public investments in key decoupling technologies like low-carbon energy, precision farming, and biotechnology. In the United States, federal institutions like the Department of Energy and ARPA-E, along with the national labs, play an important role in clean energy innovation — with more funding, they could help accelerate long-term decarbonization through cheaper and more functional nuclear and solar power, carbon capture and storage, and so forth. The same goes for the many national or international institutions for agricultural innovation, such as CGIAR. In some cases, environmental regulation or market-based mechanisms like pricing or trading schemes may spur innovation, at least of the incremental kind.[397–399] Finally, it should not be out of the question for conservation organizations to collaborate with corporations to accelerate innovation in key areas like agriculture, energy, pollution control, and water. Bt cotton, a genetically modified form of cotton that eliminates the need to use broad-spectrum insecticides, with attendant environmental advantages,[400] was developed by a private corporation.

Innovation and adoption of technology are in many cases closely related. Many environmentally benign technologies are held back in their adoption because they are too expensive, functionally inferior, or not adapted to the local context. This creates a trade-off between environmental impact and economic development that tends to be resolved in favor of the latter. To minimize this trade-off, innovation is required to make technologies cheaper, more functional, and better adapted to the needs of the users.

This applies to most of today's low-carbon energy technologies, which are generally more expensive than their fossil counterparts.[401] Without innovation to address these shortcomings, the diffusion of these technologies will remain limited. The upshot of this is that many reasons exist to innovate on low-impact technologies that do not have to do with the environment. A large share of the decoupling observed so far has been achieved not through demands for environmental protection, but as a result of the imperative to develop better, cheaper, and more abundant goods and services. This is something conservation organizations can take advantage of, by creating new coalitions with non-environmental organizations or interest groups.

4.6 LEGITIMACY, GOVERNANCE, AND CONSERVATION IN THE 21ST CENTURY

The new framework offers a strategy to achieve peak impact. The four elements all work together: decoupling through intensification and substitution, modernization, landscape planning, and innovation on the technological frontier.

No part of the broader decoupling framework can be imposed from on high. It must be embraced by societies, as well as their governing institutions. While recognizing that there will always be losses as well as gains, losers as well as winners, developmental, decoupling, and conservation efforts must all seek popular legitimacy and continuous improvements in respect for human rights and social justice.

There has been a sea change in conservation practice over the last century. Parks and protected areas, starting in the United States in the 19th century and spreading to Africa and other regions in the 20th century, were often imposed top-down with little or no consultation with local inhabitants and often involving their outright eviction.[272] Today, leading conservation NGOs have become increasingly sensitive to the needs and rights of local communities, and the need for appropriate compensation and support. Beyond greater sensitivity to local communities, conservation NGOs have over the last decades increasingly recognized the necessity of national economic development alongside conservation efforts.[11]

There has been a range of recent efforts to align economic development and conservation. In the Democratic Republic of the Congo, Virunga National Park is building a hydroelectric dam to produce power for communities living near the park with financing from the Howard Buffett Foundation.[402] The Nature Conservancy advises nations around the world on how to best site hydroelectric dams to reduce their environmental impacts.[403] And in Brazil and Southeast Asia, conservation NGOs are working with governments, multinational food companies, and local farmers to reduce deforestation by improving yields and concentrating production on already cleared land. Although in some cases it is too early to know the effects of these efforts on development and biodiversity, they are all signs that conservation organizations are already moving toward embracing decoupling and the broader framework described in this paper.

> No conservation framework can eliminate trade-offs entirely, but the goal of peak global environmental impact is realistic and inspiring — a framework with cross-national and cross-cultural appeal.

Governments, companies, and conservation NGOs all have much to gain from a framework that reduces trade-offs between development and the environment. No conservation framework can eliminate trade-offs entirely, but a goal of peak global environmental impact is realistic and potentially inspiring — a framework with cross-national and cross-cultural appeal. A better understanding and use of decoupling processes could help nations better achieve their development and conservation outcomes than the status quo. As such, we hope this framework contributes to the development of a wider, and wiser, process of modernization and conservation in the 21st century.

REFERENCES

1. Ausubel, J. H. & Waggoner, P. E. Dematerialization: Variety, caution, and persistence. *Proc. Natl. Acad. Sci. U. S. A.* **105,** 12774–12779 (2008).
2. Grossman, G. M. & Krueger, A. B. *Economic Growth and the Environment*. (National Bureau of Economic Research, 1994).
3. Shafik, N. & Bandyopadhyay, S. *Economic Growth and Environmental Quality: Time-Series and Cross-Country Evidence*. (World Bank, 1992).
4. Fisher, J. C. & Pry, R. H. A Simple Substitution Model of Technological Change. *Technol. Forecast. Soc. Change* **3,** 75–88 (1971).
5. Marchetti, C. Primary energy substitution models: On the interaction between energy and society. *Technol. Forecast. Soc. Change* **10,** 345–356 (1977).
6. Waggoner, P. E. How Much Land Can Ten Billion People Spare for Nature? *Daedalus* **125,** 73–93 (1996).
7. Goklany, I. M. & Sprague, M. W. *Sustaining Development and Biodiversity: Productivity, Efficiency, and Conservation*. (Cato Institute, 1992).
8. OECD Secretariat. *Indicators to Measure Decoupling of Environmental Pressure from Economic Growth*. (OECD, 2002).
9. UNEP. International Resource Panel. (2015). at <http://www.unep.org/resourcepanel>
10. IPCC. *Emissions Scenarios*. (Cambridge University Press, 2000).
11. Kareiva, P. & Marvier, M. What Is Conservation Science? *Bioscience* **62,** 962–969 (2012).
12. Riley, J. Estimates of Regional and Global Life Expectancy, 1800–2001. *Popul. Dev. Rev.* **31,** 537–543 (2005).
13. World Bank. Data. (2015). at <http://data.worldbank.org/>
14. Kenny, C. Why Are We Worried About Income? Nearly Everything that Matters is Converging. *World Dev.* **33,** 1–19 (2005).
15. United Nations Department of Economic and Social Affairs. World Population Prospects: The 2012 Revision. (2014). at <http://esa.un.org/wpp/>
16. Maddison, A. Historical Statistics of the World Economy: 1–2008 AD. (2008). at <http://www.ggdc.net/maddison/oriindex.htm>
17. FAO. Food Balance Sheets. *FAOSTAT* (2015). at <http://faostat3.fao.org/browse/FB/FBS/E>
18. Shiklomanov, I. World Water Resources and Their Use. (1999). at <http://webworld.unesco.org/water/ihp/db/shiklomanov/>
19. Krausmann, F. *et al.* Growth in global materials use, GDP and population during the 20th century. *Ecol. Econ.* **68,** 2696–2705 (2009).
20. Nakicenovic , N. & Grübler, A. Energy and the protection of the atmosphere. *Int. J. Glob. Energy Issues* **13,** 4–57 (2000).
21. Seto, K. C., Fragkias, M., Guneralp, B. & Reilly, M. K. A Meta-Analysis of Global Urban Land Expansion. *PLoS One* **6,** e23777 (2011).
22. Stern, P. C., Dietz, T., Ruttan, V. W., Socolow, R. H. & Sweeney, J. L. *Environmentally Significant Consumption: Research Directions*. (National Academies Press, 1997).

23. UNEP. *Decoupling Natural Resource Use and Environmental Impacts from Economic Growth*. (UNEP, 2011).

24. UNEP. *Assessing the Environmental Impacts of Consumption and Production: Priority Products and Materials*. (UNEP, 2010).

25. Maxim, L., Spangenberg, J. H. & O'Connor, M. An analysis of risks for biodiversity under the DPSIR framework. *Ecol. Econ.* **69,** 12–23 (2009).

26. Niemeijer, D. & de Groot, R. S. A conceptual framework for selecting environmental indicator sets. *Ecol. Indic.* **8,** 14–25 (2008).

27. Omann, I., Stocker, A. & Jäger, J. Climate change as a threat to biodiversity: An application of the DPSIR approach. *Ecol. Econ.* **69,** 24–31 (2009).

28. WWF. *The Living Planet Report 2014*. (WWF, 2014).

29. Loehle, C. & Eschenbach, W. Historical bird and terrestrial mammal extinction rates and causes. *Divers. Distrib.* **18,** 84–91 (2012).

30. IUCN. The IUCN Red List of Threatened Species. (2015). at <http://www.iucnredlist.org>

31. Hoffmann, M. *et al.* The Impact of Conservation on the Status of the World's Vertebrates. *Science* **330,** 1503–1509 (2010).

32. Ripple, W. J. *et al.* Status and Ecological Effects of the World's Largest Carnivores. *Science* **343,** 1241484 (2014).

33. Johnson, C. N., Bradshaw, C. J., Cooper, A., Gillespie, R. & Brook, B. W. Rapid megafaunal extinction following human arrival throughout the New World. *Quat. Int.* **308-309,** 273–277 (2013).

34. Braje, T. J. & Erlandson, J. M. Human acceleration of animal and plant Extinctions: A Late Pleistocene, Holocene, and Anthropocene continuum. *Anthropocene* **4,** 14–23 (2013).

35. Barnosky, A. D., Koch, P. L., Feranec, R. S., Wing, S. L. & Shabel, A. B. Assessing the Causes of Late Pleistocene Extinctions on the Continents. *Science* **306,** 70–75 (2004).

36. Johnson, C. Ecological consequences of Late Quaternary extinctions of megafauna. *Proc. R. Soc. B* **276,** 2509–2519 (2009).

37. Estes, J. A. *et al.* Trophic downgrading of planet Earth. *Science* **333,** 301–306 (2011).

38. Ripple, W. J. *et al.* Collapse of the world's largest herbivores. *Sci. Adv.* **1,** e1400103 (2015).

39. Wilkie, D. S., Bennett, E. L., Peres, C. A. & Cunningham, A. A. The empty forest revisited. *Ann. N. Y. Acad. Sci.* **1223,** 120–128 (2011).

40. Peres, C. A. Effects of Subsistence Hunting on Vertebrate Community Structure in Amazonian Forests. *Conserv. Biol.* **14,** 240–253 (2000).

41. Milner-Gulland, E. & Bennett, E. L. Wild meat: the bigger picture. *Trends Ecol. Evol.* **18,** 351–357 (2003).

42. Redford, K. H. The Empty Forest. *Bioscience* **42,** 412–422 (1992).

43. Fa, J. E., Peres, C. & Meeuwig, J. Bushmeat Exploitation in Tropical Forests: an Intercontinental Comparison. *Conserv. Biol.* **16,** 232–237 (2002).

44. FAO. *The State of World Fisheries and Aquaculture 2014*. (FAO, 2014).

45. Hutchings, J. A., Minto, C., Ricard, D., Baum, J. K. & Jensen, O. P. Trends in the abundance of marine fishes. *Can. J. Fish. Aquat. Sci.* **67,** 1205–1210 (2010).

46. Jackson, J. *et al.* Historical Overfishing and the Recent Collapse of Coastal Ecosystems. *Science* **293,** 629–637 (2001).

47. Dulvy, N. K., Sadovy, Y. & Reynolds, J. D. Extinction vulnerability in marine populations. *Fish Fish.* **4,** 25–64 (2003).

48. Tonnessen, J. & Johnsen, A. *The History of Modern Whaling.* (University of California Press, 1982).

49. Rocha Jr, R. C., Clapham, P. J. & Ivashchenko, Y. V. Emptying the Oceans: A Summary of Industrial Whaling Catches in the 20th Century. *Mar. Fish. Rev.* **76,** 37–48 (2014).

50. International Whaling Commission. Status of whales. (2015). at <https://iwc.int/status>

51. Still, J. Use of animal products in traditional Chinese medicine: environmental impact and health hazards. *Complement. Ther. Med.* **11,** 118–122 (2003).

52. Wittemyer, G. *et al.* Illegal killing for ivory drives global decline in African elephants. *Proc. Natl. Acad. Sci.* **111,** 13117–13121 (2014).

53. Emslie, R. Diceros bicornis. *IUCN Red List Threat. Species. Version 2014.3* (2012). at <http://www.iucnredlist.org/details/6557/0>

54. Dinerstein, E. *et al.* The Fate of Wild Tigers. *Bioscience* **57,** 508–514 (2007).

55. Hosonuma, N. *et al.* An assessment of deforestation and forest degradation drivers in developing countries. *Environ. Res. Lett.* **7,** 044009 (2012).

56. Geist, H. J. & Lambin, E. F. Proximate Causes and Underlying Driving Forces of Tropical Deforestation. *Bioscience* **52,** 143–150 (2002).

57. Specht, M. J., Pinto, S. R. R., Albuquerque, U. P., Tabarelli, M. & Melo, F. P. L. Burning biodiversity : Fuelwood harvesting causes forest degradation in human-dominated tropical landscapes. *Glob. Ecol. Conserv.* **3,** 200–209 (2015).

58. Puyravaud, J. P., Davidar, P. & Laurance, W. F. Cryptic destruction of India's native forests. *Conserv. Lett.* **3,** 390–394 (2010).

59. Ellis, E. C. Anthropogenic transformation of the terrestrial biosphere. *Philos. Trans. R. Soc. A* **369,** 1010–1035 (2011).

60. Erb, K. H. *et al.* A comprehensive global 5 min resolution land-use data set for the year 2000 consistent with national census data. *J. Land Use Sci.* **2,** 191–224 (2007).

61. Monfreda, C., Ramankutty, N. & Foley, J. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochem. Cycles* **22,** (2008).

62. Ellis, E. C., Klein Goldewijk, K., Siebert, S., Lightman, D. & Ramankutty, N. Anthropogenic transformation of the biomes, 1700 to 2000. *Glob. Ecol. Biogeogr.* **19,** 589–606 (2010).

63. Lambin, E. F. & Meyfroidt, P. Global land use change, economic globalization, and the looming land scarcity. *Proc. Natl. Acad. Sci. U. S. A.* **108,** 3465–3472 (2011).

64. Liu, Z., He, C., Zhou, Y. & Wu, J. How much of the world's land has been urbanized, really? A hierarchical framework for avoiding confusion. *Landsc. Ecol.* **29,** 763–771 (2014).

65. Angel, S., Parent, J., Civco, D. L., Blei, A. & Potere, D. The dimensions of global urban expansion: Estimates and projections for all countries, 2000–2050. *Prog. Plann.* **75,** 53–107 (2011).

66. Schneider, A., Friedl, M. A. & Potere, D. A new map of global urban extent from MODIS satellite data. *Environ. Res. Lett.* **4,** 044003 (2009).

67. FAO. Inputs - Land. *FAOSTAT* (2015). at <http://faostat3.fao.org/browse/R/RL/E>

68. FAO. *Global Forest Resources Assessment 2010*. (FAO, 2010).

69. Ramankutty, N., Evan, A. T., Monfreda, C. & Foley, J. A. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Global Biogeochem. Cycles* **22,** (2008).

70. Cassidy, E. S., West, P. C., Gerber, J. S. & Foley, J. A. Redefining agricultural yields: from tonnes to people nourished per hectare. *Environ. Res. Lett.* **8,** 034015 (2013).

71. Green, R. E., Cornell, S. J., Scharlemann, J. P. & Balmford, A. Farming and the fate of wild nature. *Science* **307,** 550–555 (2005).

72. Secretariat of the Convention on Biological Diversity. *Global Biodiversity Outlook 3*. (Convention on Biological Diversity, 2010).

73. Millennium Ecosystem Assessment. *Ecosystems and Human Well-Being Vol 1: Current State and Trends*. (Island Press, 2005).

74. Smakhtin, V., Revenga, C. & Döll, P. A pilot global assessment of environmental water requirements and scarcity. *Water Int.* **29,** 307–317 (2004).

75. Hoekstra, A., Mekonnen, M., Chapagain, A., Mathews, R. & Richter, B. Global Monthly Water Scarcity: Blue Water Footprints versus Blue Water Availability. *PLoS One* **7,** e32688 (2012).

76. Brown, L. R. *Plan B 2.0: Rescuing a Planet Under Stress and a Civilization in Trouble*. (Earth Policy Institute, 2006).

77. Konikow, L. F. & Kendy, E. Groundwater depletion: A global problem. *Hydrogeol. J.* **13,** 317–320 (2005).

78. Fabry, V. J., Seibel, B. A., Feely, R. A. & Orr, J. C. Impacts of ocean acidification on marine fauna and ecosystem processes. *ICES J. Mar. Sci.* **65,** 414–432 (2008).

79. Bouwman, A. F., Vuuren, D. P. V. A. N., Derwent, R. G. & Posch, M. A global analysis of acidification and eutrophication of terrestrial ecosystems. *Water. Air. Soil Pollut.* **141,** 349–382 (2002).

80. Erisman, J. W. *et al.* Consequences of human modification of the global nitrogen cycle. *Philos. Trans. R. Soc. B Biol. Sci.* **368,** 20130116 (2013).

81. Diaz, R. J. & Rosenberg, R. Spreading Dead Zones and Consequences for Marine Ecosystems. *Science* **321,** 926–929 (2008).

82. Parmesan, C. & Yohe, G. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* **421,** 37–42 (2003).

83. Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W. & Courchamp, F. Impacts of climate change on the future of biodiversity. *Ecol. Lett.* **15,** 365–377 (2012).

84. Harley, C. D. *et al.* The impacts of climate change in coastal marine systems. *Ecol. Lett.* **9,** 228–241 (2006).

85. Galbraith, H. *et al.* Global Climate Change and Sea Level Rise: Potential Losses of Intertidal Habitat for Shorebirds. *Waterbirds* **25,** 173–183 (2002).

86. Waggoner, P. E. & Ausubel, J. H. A framework for sustainability science: A renovated IPAT identity. *Proc. Natl. Acad. Sci. U. S. A.* **99,** 7860–7865 (2002).

87. Ehrlich, P. R. & Holdren, J. A Bulletin Dialogue on' The Closing Circle,' Critique. *Bull. At. Sci.* **28,** 16–27 (1972).
88. Commoner, B. *The Closing Circle: Nature, Man, and Technology*. (Alfred A. Knopf, Inc., 1971).
89. Schaffartzik, A., Eisenmenger, N., Krausmann, F. & Weisz, H. Consumption-based Material Flow Accounting. *J. Ind. Ecol.* **18,** 102–112 (2014).
90. Gerbens-Leenes, P., Nonhebel, S. & Krol, M. Food consumption patterns and economic growth. Increasing affluence and the use of natural resources. *Appetite* **55,** 597–608 (2010).
91. International Monetary Fund. *World Economic Outlook April 2011*. (IMF, 2011).
92. Grübler, A. *Technology and Global Change*. (Cambridge University Press, 2003).
93. Huber, J. *New Technologies and Environmental Innovation*. (Edward Elgar Publishing, 2004).
94. Alcott, B. Jevons' paradox. *Ecol. Econ.* **54,** 9–21 (2005).
95. Dahmus, J. B. Can Efficiency Improvements Reduce Resource Consumption? *J. Ind. Ecol.* **18,** 883–897 (2014).
96. Kearney, J. Food consumption trends and drivers. *Philos. Trans. R. Soc. London B Biol. Sci.* **365,** 2793–2807 (2010).
97. Kastner, T., Rivas, M. J. I., Koch, W. & Nonhebel, S. Global changes in diets and the consequences for land requirements for food. *Proc. Natl. Acad. Sci. U. S. A.* **109,** 6868–6872 (2012).
98. Foley, J. A. *et al.* Solutions for a cultivated planet. *Nature* **478,** 337–342 (2011).
99. Ray, D. K. & Foley, J. A. Increasing global crop harvest frequency: recent trends and future directions. *Environ. Res. Lett.* **8,** 044041 (2013).
100. Steinfeld, H. & Gerber, P. Livestock production and the global environment: Consume less or produce better? *Proc. Natl. Acad. Sci. U. S. A.* **107,** 18237–18238 (2010).
101. Capper, J. L. & Bauman, D. E. The Role of Productivity in Improving the Environmental Sustainability of Ruminant Production Systems. *Annu. Rev. Anim. Biosci.* **1,** 469–489 (2013).
102. Smil, V. *Should We Eat Meat? Evolution and Consequences of Modern Carnivory*. (John Wiley & Sons, Ltd., 2013).
103. Capper, J. L. The environmental impact of beef production in the United States: 1977 compared with 2007. *J. Anim. Sci.* **89,** 4249–4261 (2011).
104. FAO. Forestry. *FAOSTAT* (2015). at <http://faostat3.fao.org/browse/F/*/E>
105. Fox, T. R. Sustained productivity in intensively managed forest plantations. *For. Ecol. Manage.* **138,** 187–202 (2000).
106. FAO. *State of the World's Forests*. (FAO, 2011).
107. Kauppi, P. E. *et al.* Returning forests analyzed with the forest identity. *Proc. Natl. Acad. Sci. U. S. A.* **103,** 17574-17579 (2006).
108. Paquette, A. & Messier, C. The role of plantations in managing the world's forests in the Anthropocene. *Front. Ecol. Environ.* **8,** 27–34 (2010).
109. Warman, R. D. Global wood production from natural forests has peaked. *Biodivers. Conserv.* **23,** 1063–1078 (2014).

110. Ellis, E. C. *et al.* Estimating Long-Term Changes in China's Village Landscapes. *Ecosystems* **12,** 279–297 (2009).

111. Song, W. & Liu, M. Assessment of decoupling between rural settlement area and rural population in China. *Land use policy* **39,** 331–341 (2014).

112. Angel, S., Parent, J., Civco, D. L., Blei, A. & Potere, D. The dimensions of global urban expansion: Estimates and projections for all countries, 2000–2050. *Prog. Plann.* **75,** 53–107 (2011).

113. Ruddiman, W. F. & Ellis, E. C. Effect of per-capita land use changes on Holocene forest clearance and CO2 emissions. *Quat. Sci. Rev.* **28,** 3011–3015 (2009).

114. Lawson, K. & Vines, A. *Global Impacts of the Illegal Wildlife Trade: The Costs of Crime, Insecurity and Institutional Erosion*. (Chatham House, 2014).

115. CITES. *Monitoring the Illegal Killing of Elephants: Update on Elephant Poaching Trends in Africa to 31 December 2014*. (CITES, 2014).

116. Emslie, R. H. *African Rhinoceroses – Latest trends in rhino numbers and poaching*. (IUCN, 2013).

117. Biggs, D., Courchamp, F., Martin, R. & Possingham, H. Legal Trade of Africa's Rhino Horns. *Science* **339,** 1038–1039 (2013).

118. WESSA. Current Rhino Poaching Stats. (2015). at <http://wessa.org.za/get-involved/rhino-initiative/current-rhino-poaching-stats.htm>

119. Sharma, K., Wright, B., Joseph, T. & Desai, N. Tiger poaching and trafficking in India: Estimating rates of occurrence and detection over four decades. *Biol. Conserv.* **179,** 33–39 (2014).

120. International Whaling Commission. Total catches. (2015). at <https://iwc.int/total-catches>

121. Yang, C. & Cui, X. Global Changes and Drivers of the Water Footprint of Food Consumption: A Historical Analysis. *Water* **6,** 1435–1452 (2014).

122. Nordhaus, T., Shellenberger, M. & Blomqvist, L. *The Planetary Boundaries Hypothesis: A Review of the Evidence*. (Breakthrough Institute, 2012).

123. IPCC. *Climate Change 2014: Synthesis Report*. (IPCC, 2014).

124. BP. Historical Data Workbook. *Stat. Rev. World Energy 2014* (2014). at <http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy.html>

125. Afsah, S. & Salcito, K. Global Carbon Intensity: How China Wrecked this Metric. (2014). at <http://co2scorecard.org/home/researchitem/31>

126. EIA. International Energy Statistics. (2015). at <http://www.eia.gov/beta/international/data/browser/>

127. IIASA. RCP Database (Version 2.0.5). (2015). at <http://tntcat.iiasa.ac.at/RcpDb>

128. UNEP. *Global Environment Outlook 5: Environment for the future we want*. (UNEP, 2012).

129. The Royal Society. *Ground-level ozone in the 21st century: future trends, impacts and policy implications*. (The Royal Society, 2008).

130. Cooper, O. R. *et al.* Global distribution and trends of tropospheric ozone: An observation-based review. *Elem. Sci. Anthr.* **2,** 000029 (2014).

131. Hung, H. *et al.* Atmospheric monitoring of organic pollutants in the Arctic under the Arctic Monitoring and Assessment Programme (AMAP): 1993-2006. *Sci. Total Environ.* **408,** 2854–2873 (2010).

132. Rudel, T. K. *Tropical Forests: Regional Paths of Destruction and Regeneration in the Late Twentieth Century*. (Columbia University Press, 2005).

133. Angelsen, A. Policies for reduced deforestation and their impact on agricultural production. *Proc. Natl. Acad. Sci. U. S. A.* **107,** 19639–19644 (2010).

134. Chomitz, K. M. & Kumari, K. The Domestic Benefits of Tropical Forests: A Critical Review. *World Bank Res. Obs.* **13,** 13–35 (1998).

135. Hertel, T. W., Ramankutty, N. & Baldos, U. L. C. Global market integration increases likelihood that a future African Green Revolution could increase crop land use and CO2 emissions. *Proc. Natl. Acad. Sci. U. S. A.* **111,** 13799–13804 (2014).

136. Navarro, L. M. & Pereira, H. M. Rewilding Abandoned Landscapes in Europe. *Ecosystems* **15,** 900–912 (2012).

137. Juffe-Bignoli, D. *et al. Protected Planet Report 2014*. (UNEP-WCMC, 2014).

138. Pearce, D. Environmental market creation: saviour or oversell? *Port. Econ. J.* **3,** 115–144 (2004).

139. Fisher, B., Edwards, D. P., Giam, X. & Wilcove, D. S. The high costs of conserving Southeast Asia's lowland rainforests. *Front. Ecol. Environ.* **9,** 329–334 (2011).

140. Mittermeier, R. A. *et al.* Wilderness and biodiversity conservation. *Proc. Natl. Acad. Sci. U. S. A.* **100,** 10309–10313 (2003).

141. Pearce, D. Paradoxes in Biodiversity Conservation. *World Econ.* **6,** 57–70 (2005).

142. Ferraro, P. J. & Kiss, A. Direct Payments to Conserve Biodiversity. *Science* **298,** 1718–1719 (2002).

143. Secretariat of the Convention on Biological Diversity. *Global Biodiversity Outlook 3*. (Convention on Biological Diversity, 2010).

144. Boyd, J. W. & Banzhaf, S. What are ecosystem services? The need for standardized environmental accounting units. *Ecol. Econ.* **63,** 616–626 (2007).

145. Zhang, W., Ricketts, T. H., Kremen, C., Carney, K. & Swinton, S. M. Ecosystem services and dis-services to agriculture. *Ecol. Econ.* **64,** 253–260 (2007).

146. Power, A. G. Ecosystem services and agriculture: tradeoffs and synergies. *Philos. Trans. R. Soc. London B Biol. Sci.* **365,** 2959–2971 (2010).

147. Ayres, R. U. On the practical limits to substitution. *Ecol. Econ.* **61,** 115–128 (2007).

148. Tilman, D., Balzer, C., Hill, J. & Befort, B. L. Global food demand and the sustainable intensification of agriculture. *Proc. Natl. Acad. Sci. U. S. A.* **108,** 20260–20264 (2011).

149. Cleveland, C. J. The direct and indirect use of fossil fuels and electricity in USA agriculture, 1910–1990. *Agric. Ecosyst. Environ.* **55,** 111–121 (1995).

150. Pelletier, N. *et al.* Energy Intensity of Agriculture and Food Systems. *Annu. Rev. Environ. Resour.* **36,** 223–246 (2011).

151. Tyedmers, P. & Pelletier, N. Biophysical accounting in aquaculture: insights from current practice and the need for methodological development. *FAO Fish. Proc.* **10,** 229–241 (2007).

152. Woods, J., Williams, A., Hughes, J. K., Black, M. & Murphy, R. Energy and the food system. *Philos. Trans. R. Soc. London B Biol. Sci.* **365,** 2991–3006 (2010).

153. Leach, G. *Energy and food production*. (IPC Science and Technology Press Ltd., 1976).

154. Smil, V. *Energy in Nature and Society: General Energetics of Complex Systems*. (MIT Press, 2008).

155. Schneider, U. A. & Smith, P. Energy intensities and greenhouse gas emission mitigation in global agriculture. *Energy Effic.* **2,** 195–206 (2009).

156. Ellis, E. C. *et al.* Used Planet: A Global History. *Proc. Natl. Acad. Sci. U. S. A.* **110,** 7978–7985 (2013).

157. Wayne, F. Deferred Harvests: The Transition from Hunting to Animal Husbandry. *American Anthropologist* **103,** 295–311 (2001).

158. Elferink, E. V. V & Nonhebel, S. Variations in land requirements for meat production. *J. Clean. Prod.* **15,** 1778–1786 (2007).

159. Capper, J. L. Is the Grass Always Greener? Comparing the Environmental Impact of Conventional, Natural and Grass-Fed Beef Production Systems. *Animals* **2,** 127–143 (2012).

160. Reeves, R. R. & Smith, T. D. in *Whales, Whaling, Ocean Ecosyst.* (eds. Estes, J., DeMaster, D., Doak, D., Williams, T. & Brownell Jr, R.) 82–101 (University of California Press, 2006).

161. Davis, L., Gallman, R. & Gleiter, K. *In Pursuit of Leviathan: Technology, Institutions, Productivity, and Profits in American Whaling, 1816-1906*. (University of Chicago Press, 1997).

162. Tower, W. S. *A History of the American Whale Fishery*. (University of Pennsylvania, 1907).

163. Bezanson, A., Gray, R. D. & Hussey, M. *Wholesale Prices in Philadelphia, 1852-1896*. (University of Pennsylvania Press, 1936).

164. Williamson, H. F. *The American Petroleum Industry; The Age of Illumination, 1859-1899*. (Northwestern University Press, 1959).

165. Dolin, E. *Leviathan: The History of Whaling in America*. (WW Norton & Company, 2008).

166. Naylor, R. L. *et al.* Effect of aquaculture on world fish supplies. *Nature* **405,** 1017–1024 (2000).

167. Naylor, R. L. *et al.* Feeding aquaculture in an era of finite resources. *Proc. Natl. Acad. Sci. U. S. A.* **106,** 15103–15110 (2009).

168. Tacon, A. G. J. & Metian, M. Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects. *Aquaculture* **285,** 146–158 (2008).

169. Ausubel, J. H. The great reversal: nature's chance to restore land and sea. *Technol. Soc.* **22,** 289–301 (2000).

170. Diana, J. S. Aquaculture Production and Biodiversity Conservation. *Bioscience* **59,** 27–38 (2009).

171. Primavera, J. H. Overcoming the impacts of aquaculture on the coastal zone. *Ocean Coast. Manag.* **49,** 531–545 (2006).

172. Alongi, D. M. Present state and future of the world's mangrove forests. *Environ. Conserv.* **29,** 331–349 (2002).

173. Edwards, P. Aquaculture environment interactions: Past, present and likely future trends. *Aquaculture* (2015). doi:10.1016/j.aquaculture.2015.02.001

174. Neori, A. *et al.* Integrated aquaculture: Rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. *Aquaculture* **231,** 361–391 (2004).

175. Cao, L. *et al.* Environmental Impact of Aquaculture and Countermeasures to Aquaculture Pollution in China. *Environ. Sci. Pollut. Res. Int.* **14,** 452–462 (2007).

176. FAO. Aquaculture can grow faster, raising micronutrient supply from fish. (2014). at <http://www.fao.org/news/story/en/item/265790/icode/>

177. Smil, V. *Harvesting the Biosphere: What We Have Taken from Nature*. (MIT Press, 2012).

178. Williams, M. Clearing the United States forests: pivotal years 1810-1860. *J. Hist. Geogr.* **8,** 12–28 (1982).

179. Williams, M. Industrial Impacts on the Forests of the United States, 1860–1920. *J. For. Hist.* **31,** 108–121 (1987).

180. Sieferle, R. P. *The Subterranean Forest: Energy Systems and the Industrial Revolution*. (White Horse Press, 2001).

181. Reynolds, R. & Pierson, A. H. Fuel Wood Used in the United States 1630-1930. *USDA Circ.* (1942).

182. Madureira, N. L. The iron industry energy transition. *Energy Policy* **50,** 24–34 (2012).

183. Lowenthal, D. *Forest Stewardship: Marsh, Pinchot, and America Today*. (Pinchot Institute for Conservation, 2001).

184. Williams, M. Industrial impacts on the forests of the United States, 1860–1920. *J. For. Hist.* **31,** 108–121 (1987).

185. Grubler, A. & Cleveland, C. J. Energy Transitions. *Encycl. Earth* (2008).

186. IEA. *World Energy Outlook 2014*. (IEA, 2014).

187. Meyfroidt, P. & Lambin, E. F. Global Forest Transition: Prospects for an End to Deforestation. *Annu. Rev. Environ. Resour.* **36,** 343–371 (2011).

188. Wrigley, E. *Energy and the English Industrial Revolution*. (Cambridge University Press, 2010).

189. Smil, V. *Power Density: A Key to Understanding Energy Sources and Uses*. (MIT Press, 2015).

190. International Renewable Energy Agency. *Statistical issues: bioenergy and distributed renewable energy*. (IREA, 2013).

191. Smil, V. *Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production*. (MIT Press, 2001).

192. Crews, T. & Peoples, M. Legume versus fertilizer sources of nitrogen: ecological tradeoffs and human needs. *Agric. Ecosyst. Environ.* **102,** 279–297 (2004).

193. Connor, D. Organic agriculture cannot feed the world. *F. Crop. Res.* **106,** 187–190 (2008).

194. Connor, D. J. Organically grown crops do not a cropping system make and nor can organic agriculture nearly feed the world. *F. Crop. Res.* **144,** 145–147 (2013).

195. Rutkow, E. *American Canopy: Trees, Forests, and the Making of a Nation*. (Simon & Schuster, 2012).

196. Thelen, R. *The Substitution of Other Materials for Wood*. (Government Printing Office, 1917).

197. Goklany, I. M. in *Princet. Guid. to Ecol.* (eds. Levin, S. A. et al.) 659–669 (Princeton University Press, 2009).

198. Petersen, A. & Solberg, B. Environmental and economic impacts of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden. *For. Policy Econ.* **7,** 249–259 (2005).

199. International Rubber Study Group. Rubber Statistical Bulletin. (2013). at <http://www.rubberstudy.com>

200. Van Beilen, J. B. & Poirier, Y. Establishment of new crops for the production of natural rubber. *TRENDS Biotechnol.* **25,** 522–529 (2007).

201. FAO/ICAC. *World apparel fiber consumption survey*. (FAO/ICAC, 2013).

202. FAO. Production. *FAOSTAT* (2015). at <http://faostat3.fao.org/browse/Q/*/E>

203. Australian Bureau of Statistics. The wool industry - looking back and forward. *Year B. Aust. 2003* (2003). at <http://www.abs.gov.au/ausstats/abs@.nsf/Previousproducts/1301.0Feature Article172003>

204. Hoffmann, D., Nari, J. & Petheram, R. *Draught animals in rural development*. (Australian Centre for International Agricultural Research, 1989).

205. Phalan, B., Green, R. & Balmford, A. Closing yield gaps: perils and possibilities for biodiversity conservation. *Philos. Trans. R. Soc. London B Biol. Sci.* **369,** 20120285 (2014).

206. Krebs, J., Wilson, J., Bradbury, R. & Siriwardena, G. The second Silent Spring? *Nature* **400,** 611–612 (1999).

207. Phalan, B., Balmford, A., Green, R. E. & Scharlemann, J. P. Minimising the harm to biodiversity of producing more food globally. *Food Policy* **36,** S62–S71 (2011).

208. Byerlee, D., Stevenson, J. & Villoria, N. Does intensification slow crop land expansion or encourage deforestation? *Glob. Food Sec.* **3,** 92–98 (2014).

209. Rudel, T. K. *et al.* Agricultural intensification and changes in cultivated areas, 1970-2005. *Proc. Natl. Acad. Sci. U. S. A.* **106,** 20675–20680 (2009).

210. Von Wehrden, H. *et al.* Realigning the land-sharing/land-sparing debate to match conservation needs: considering diversity scales and land-use history. *Landsc. Ecol.* **29,** 941–948 (2014).

211. Ramankutty, N. & Rhemtulla, J. Can intensive farming save nature? *Front. Ecol. Environ.* **10,** 455–455 (2012).

212. Gibbs, H. K. *et al.* Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *Proc. Natl. Acad. Sci. U. S. A.* **107,** 16732–16737 (2010).

213. Chazdon, R. L. *et al.* The Potential for Species Conservation in Tropical Secondary Forests. *Conserv. Biol.* **23,** 1406–1417 (2009).

214. Gardner, T. A. *et al.* Prospects for tropical forest biodiversity in a human-modified world. *Ecol. Lett.* **12,** 561–582 (2009).

215. Putz, F. E. *et al.* Sustaining conservation values in selectively logged tropical forests: the attained and the attainable. *Conserv. Lett.* **5,** 296–303 (2012).

216. Fisher, B. *et al.* Cost-effective conservation: calculating biodiversity and logging trade-offs in Southeast Asia. *Conserv. Lett.* **4,** 443–450 (2011).

217. Gibson, L. *et al.* Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature* **478,** 378–381 (2011).

218. Sodhi, N. S., Lee, T. M., Koh, L. P. & Brook, B. W. A Meta-Analysis of the Impact of Anthropogenic Forest Disturbance on Southeast Asia's Biotas. *Biotropica* **41,** 103–109 (2009).

219. Dunn, R. R. Recovery of Faunal Communities During Tropical Forest Regeneration. *Conserv. Biol.* **18,** 302–309 (2004).

220. Dent, D. H. & Wright, S. J. The future of tropical species in secondary forests: A quantitative review. *Biol. Conserv.* **142,** 2833–2843 (2009).

221. Van Breugel, M. *et al.* Succession of ephemeral secondary forests and their limited role for the conservation of floristic diversity in a human-modified tropical landscape. *PLoS One* **8,** e82433 (2013).

222. Wilcox, B. & Murphy, D. Conservation Strategy: The Effects of Fragmentation on Extinction. *Am. Nat.* **125,** 879–887 (1985).

223. Gibson, L. *et al.* Near-Complete Extinction of Native Small Mammal Fauna 25 Years After Forest Fragmentation. *Science* **341,** 1508–1510 (2013).

224. Edwards, D. P. *et al.* Wildlife-friendly oil palm plantations fail to protect biodiversity effectively. *Conserv. Lett.* **3,** 236–242 (2010).

225. Phalan, B., Onial, M., Balmford, A. & Green, R. E. Reconciling Food Production and Biodiversity Conservation: Land Sharing and Land Sparing Compared. *Science* **333,** 1289–1291 (2011).

226. Edwards, D. P. *et al.* Land-sharing versus land-sparing logging: reconciling timber extraction with biodiversity conservation. *Glob. Chang. Biol.* **20,** 183–191 (2014).

227. Tittler, R., Messier, C. & Fall, A. Concentrating anthropogenic disturbance to balance ecological and economic values: applications to forest management. *Ecol. Appl.* **22,** 1268–1277 (2012).

228. Soga, M., Yamaura, Y., Koike, S. & Gaston, K. J. Land sharing vs. land sparing: does the compact city reconcile urban development and biodiversity conservation? *J. Appl. Ecol.* **51,** 1378–1386 (2014).

229. Sushinsky, J. R., Rhodes, J. R., Possingham, H. P., Gill, T. K. & Fuller, R. A. How should we grow cities to minimize their biodiversity impacts? *Glob. Chang. Biol.* **19,** 401–410 (2013).

230. Dorrough, J., Moll, J. & Crosthwaite, J. Can intensification of temperate Australian livestock production systems save land for native biodiversity? *Agric. Ecosyst. Environ.* **121,** 222–232 (2007).

231. Alkemade, R., Reid, R. S., van den Berg, M., de Leeuw, J. & Jeuken, M. Assessing the impacts of livestock production on biodiversity in rangeland ecosystems. *Proc. Natl. Acad. Sci. U. S. A.* **110,** 20900–20905 (2013).

232. Queiroz, C., Beilin, R., Folke, C. & Lindborg, R. Farmland abandonment: threat or opportunity for biodiversity conservation? A global review. *Front. Ecol. Environ.* **12,** 288–296 (2014).

233. Ewers, R. M., Scharlemann, J. P. ., Balmford, A. & Green, R. E. Do increases in agricultural yield spare land for nature? *Glob. Chang. Biol.* **15,** 1716–1726 (2009).

234. Phelps, J., Carrasco, L. R., Webb, E. L., Koh, L. P. & Pascual, U. Agricultural intensification escalates future conservation costs. *Proc. Natl. Acad. Sci. U. S. A.* **110,** 7601–7606 (2013).

235. Ceddia, M. G., Bardsley, N. O., Gomez-Y-Paloma, S. & Sedlacek, S. Governance, agricultural intensification, and land sparing in tropical South America. *Proc. Natl. Acad. Sci. U. S. A.* **111,** 7242–7247 (2014).

236. Carrasco, L., Larrosa, C., Milner-Gulland, E. & Edwards, D. A double-edged sword for tropical forests. *Science* **346,** 38–40 (2014).

237. Pfaff, A. & Walker, R. Regional interdependence and forest 'transitions': Substitute deforestation limits the relevance of local reversals. *Land Use Policy* **27,** 119–129 (2010).

238. Grau, R., Kuemmerle, T. & Macchi, L. Beyond 'land sparing versus land sharing': environmental heterogeneity, globalization and the balance between agricultural production and nature conservation. *Curr. Opin. Environ. Sustain.* **5,** 477–483 (2013).

239. Conant, R. T., Berdanier, A. B. & Grace, P. R. Patterns and trends in nitrogen use and nitrogen recovery efficiency in world agriculture. *Global Biogeochem. Cycles* **27,** 558–566 (2013).

240. Frink, C. R., Waggoner, P. E. & Ausubel, J. H. Nitrogen fertilizer: Retrospect and prospect. *Proc. Natl. Acad. Sci. U. S. A.* **96,** 1175–1180 (1999).

241. Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J. & Garnier, J. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. *Environ. Res. Lett.* **9,** 105011 (2014).

242. OECD. *OECD Compendium of Agri-environmental Indicators*. (OECD Publishing, 2013).

243. Cassman, K. G. Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. *Proc. Natl. Acad. Sci. U. S. A.* **96,** 5952–5959 (1999).

244. Wilkinson, B. H. Humans as geologic agents: A deep-time perspective. *Geology* **33,** 161–164 (2005).

245. FAO. *The State of the World's Land and Water Resources for Food and Agriculture: Managing Systems at Risk*. (Earthscan, 2011).

246. Montgomery, D. R. Soil erosion and agricultural sustainability. *Proc. Natl. Acad. Sci. U. S. A.* **104,** 13268–13272 (2007).

247. Ruttan, V. W. The transition to agricultural sustainability. *Proc. Natl. Acad. Sci. U. S. A.* **96,** 5960–5967 (1999).

248. Burney, J. A., Davis, S. J. & Lobell, D. B. Greenhouse gas mitigation by agricultural intensification. *Proc. Natl. Acad. Sci. U. S. A.* **107,** 12052–12057 (2010).

249. Palm, C. A. *et al.* Identifying potential synergies and trade-offs for meeting food security and climate change objectives in sub-Saharan Africa. *Proc. Natl. Acad. Sci. U. S. A.* **107,** 19661–19666 (2010).

250. Flynn, H. C. *et al.* Quantifying global greenhouse gas emissions from land-use change for crop production. *Glob. Chang. Biol.* **18,** 1622–1635 (2012).

251. West, P. C. *et al.* Trading carbon for food: global comparison of carbon stocks vs. crop yields on agricultural land. *Proc. Natl. Acad. Sci. U. S. A.* **107,** 19645–19648 (2010).

252. Wallace, J. S. Increasing agricultural water use efficiency to meet future food production. *Agric. Ecosyst. Environ.* **82,** 105–119 (2000).

253. Gustafson, D. I. *et al.* Climate adaptation imperatives: Global sustainability trends and eco-efficiency metrics in four major crops - canola, cotton, maize, and soybeans. *Int. J. Agric. Sustain.* **12,** 146–163 (2014).

254. Kirchmann, H. & Bergström, L. Do organic farming practices reduce nitrate leaching? *Commun. Soil Sci. Plant Anal.* **32,** 997–1028 (2001).

255. Mondelaers, K., Aertsens, J. & Van Huylenbroeck, G. A meta-analysis of the differences in environmental impacts between organic and conventional farming. *Br. Food J.* **111,** 1098–1119 (2009).

256. Tuomisto, H. L., Hodge, I. D., Riordan, P. & Macdonald, D. W. Does organic farming reduce environmental impacts? - A meta-analysis of European research. *J. Environ. Manage.* **112,** 309–320 (2012).

257. Juffe-Bignoli, D. *et al. Protected Planet Report 2014*. (UNEP, 2014).

258. Joppa, L. N. & Pfaff, A. High and Far: Biases in the Location of Protected Areas. *PLoS One* **4,** e8273 (2009).

259. Naughton-Treves, L., Holland, M. B. & Brandon, K. The Role of Protected Areas in Conserving Biodiversity and Sustaining Local Livelihoods. *Annu. Rev. Environ. Resour.* **30,** 219–252 (2005).

260. Andam, K. S., Ferraro, P. J., Pfaff, A., Sanchez-Azofeifa, G. A. & Robalino, J. A. Measuring the effectiveness of protected area networks in reducing deforestation. *Proc. Natl. Acad. Sci. U. S. A.* **105,** 16089–16094 (2008).

261. Mascia, M. B. & Pailler, S. Protected area downgrading, downsizing, and degazettement (PADDD) and its conservation implications. *Conserv. Lett.* **4,** 9–20 (2011).

262. Mascia, M. B. *et al.* Protected area downgrading, downsizing, and degazettement (PADDD) in Africa, Asia, and Latin America and the Caribbean, 1900–2010. *Biol. Conserv.* **169,** 355–361 (2014).

263. Bernard, E., Penna, L. A. O. & Araújo, E. Downgrading, Downsizing, Degazettement, and Reclassification of Protected Areas in Brazil. *Conserv. Biol.* **28,** 939–950 (2014).

264. Leverington, F., Costa, K. L., Pavese, H., Lisle, A. & Hockings, M. A Global Analysis of Protected Area Management Effectiveness. *Environ. Manage.* **46,** 685–698 (2010).

265. Clark, N. E., Boakes, E. H., McGowan, P. J. K., Mace, G. M. & Fuller, R. A. Protected Areas in South Asia Have Not Prevented Habitat Loss: A Study Using Historical Models of Land-Use Change. *PLoS One* **8,** e65298 (2013).

266. Balmford, A. & Whitten, T. Who should pay for tropical conservation, and how could the costs be met? *Oryx* **37,** 238–250 (2003).

267. Adams, W. M. *et al.* Biodiversity Conservation and the Eradication of Poverty. *Science* **306,** 1146–1149 (2004).

268. Pullin, A. S. *et al.* Human well-being impacts of terrestrial protected areas. *Environ. Evid.* **2,** 19 (2013).

269. Coad, L., Campbell, A., Miles, L. & Humphries, K. *The Costs and Benefits of Forest Protected Areas for Local Livelihoods: a review of the current literature*. (UNEP-WCMC, 2008).

270. Ferraro, P. J. & Hanauer, M. M. Protecting Ecosystems and Alleviating Poverty with Parks and Reserves: 'Win-Win' or Tradeoffs? *Environ. Resour. Econ.* **48,** 269–286 (2010).

271. Pullin, A. S. *et al.* Human well-being impacts of terrestrial protected areas. *Environ. Evid.* **2,** 19 (2013).

272. Dowie, M. *Conservation Refugees: The Hundred-Year Conflict between Global Conservation and Native Peoples*. (MIT Press, 2009).

273. Cernea, M. & Schmidt-Soltau, K. Poverty Risks and National Parks: Policy Issues in Conservation and Resettlement. *World Dev.* **34,** 1808–1830 (2006).

274. Norton-Griffiths, M. & Southey, C. The opportunity costs of biodiversity conservation in Kenya. *Ecol. Econ.* **12,** 125–139 (1995).

275. Tumusiime, D. M. & Vedeld, P. Can biodiversity conservation benefit local people? Costs and benefits at a strict Protected Area in Uganda. *J. Sustain. For.* DOI:10.1080/10549811.2015.1038395 (2015).

276. Andam, K. S., Ferraro, P. J., Sims, K. R. E., Healy, A. & Holland, M. B. Protected areas reduced poverty in Costa Rica and Thailand. *Proc. Natl. Acad. Sci. U. S. A.* **107,** 9996–10001 (2010).

277. Canavire-Bacarreza, G. & Hanauer, M. M. Estimating the Impacts of Bolivia's Protected Areas on Poverty. *World Dev.* **41,** 265–285 (2013).

278. Hutton, J., Adams, W. M. & Murombedzi, J. C. Back to the Barriers? Changing Narratives in Biodiversity Conservation. *Forum Dev. Stud.* **32,** 341–370 (2005).

279. James, A. & Gaston, K. J. Can we afford to conserve biodiversity? *Bioscience* **51,** 43–52 (2001).

280. Aukland, L., Costa, P. M., Brown, S. & Moura, P. A conceptual framework and its application for addressing leakage: the case of avoided deforestation. *Clim. Policy* **3,** 123–136 (2003).

281. Henders, S. & Ostwald, M. Forest Carbon Leakage Quantification Methods and Their Suitability for Assessing Leakage in REDD. *Forests* **3,** 33–58 (2012).

282. Oliveira, P. J. C. *et al.* Land-Use Allocation Protects the Peruvian Amazon. *Science* **317,** 1233–1236 (2007).

283. Ewers, R. M. & Rodrigues, A. S. L. Estimates of reserve effectiveness are confounded by leakage. *Trends Ecol. Evol.* **23,** 113–116 (2008).

284. DeFries, R., Hansen, A., Newton, A. C. & Hansen, M. C. Increasing isolation of protected areas in tropical forests over the past twenty years. *Ecol. Appl.* **15,** 19–26 (2005).

285. Dewi, S., van Noordwijk, M., Ekadinata, A. & Pfund, J. L. Protected areas within multifunctional landscapes: Squeezing out intermediate land use intensities in the tropics? *Land use policy* **30,** 38–56 (2013).

286. Meyfroidt, P., Rudel, T. K. & Lambin, E. F. Forest transitions, trade, and the global displacement of land use. *Proc. Natl. Acad. Sci. U. S. A.* **107,** 20917–20922 (2010).

287. Meyfroidt, P., Lambin, E. F., Erb, K. H. & Hertel, T. W. Globalization of land use: distant drivers of land change and geographic displacement of land use. *Curr. Opin. Environ. Sustain.* **5,** 438–444 (2013).

288. Mayer, A. L., Kauppi, P. E., Angelstam, P. K., Zhang, Y. & Tikka, P. M. Importing Timber, Exporting Ecological Impact. *Science* **308,** 359–360 (2005).

289. Murray, B., McCarl, B. & Lee, H. Estimating Leakage from Forest Carbon Sequestration Programs. *Land Econ.* **80,** 109–124 (2004).

290. Berlik, M., Kittredge, D. & Foster, D. The illusion of preservation: a global environmental argument for the local production of natural resources. *J. Biogeogr.* **29,** 1557–1568 (2002).

291. Ferraro, P. J., Hanauer, M. M. & Sims, K. R. E. Conditions associated with protected area success in conservation and poverty reduction. *Proc. Natl. Acad. Sci. U. S. A.* **108,** 13913–13918 (2011).

292. Peters, C., Gentry, A. & Mendelsohn, R. Valuation of an Amazonian rainforest. *Nature 339, 655-656* (1989).

293. Tallis, H., Kareiva, P., Marvier, M. & Chang, A. An ecosystem services framework to support both practical conservation and economic development. *Proc. Natl. Acad. Sci. U. S. A.* **105,** 9457–9464 (2008).

294. Nepstad, D. C. & Schwartzman, S. *Non-timber Forest Products from Tropical Forests: Evaluation of a Conservation and Development Strategy*. (The New York Botanical Garden, 1992).

295. Pokorny, B., Johnson, J., Medina, G. & Hoch, L. Market-based conservation of the Amazonian forests: Revisiting win–win expectations. *Geoforum* **43,** 387–401 (2012).

296. Vedeld, P., Angelsen, A., Bojö, J., Sjaastad, E. & Berg, G. K. Forest environmental incomes and the rural poor. *For. Policy Econ.* **9,** 869–879 (2007).

297. Ambrose-Oji, B. The contribution of NTFPs to the livelihoods of the 'forest poor': evidence from the tropical forest zone of south-west Cameroon. *Int. For. Rev.* **5,** 106–117 (2003).

298. Arnold, J. E. M. & Pérez, M. R. Can non-timber forest products match tropical forest conservation and development objectives? *Ecol. Econ.* **39,** 437–447 (2001).

299. Sunderlin, W. D. *et al.* Livelihoods, Forests, and Conservation in Developing Countries: An Overview. *World Dev.* **33,** 1383–1402 (2005).

300. Kusters, K., Achdiawan, R., Belcher, B. & Pérez, M. R. Balancing Development and Conservation? An assessment of Livelihood and Environmental Outcomes of Nontimber Forest Product Trade in Asia, Africa, and Latin America. *Ecol. Soc.* **11,** 20 (2006).

301. Crook, C. & Clapp, R. A. Is market-oriented forest conservation a contradiction in terms? *Environ. Conserv.* **25,** 131–145 (1998).

302. Belcher, B., Ruíz-Pérez, M. & Achdiawan, R. Global Patterns and Trends in the Use and Management of Commercial NTFPs: Implications for Livelihoods and Conservation. *World Dev.* **33,** 1435–1452 (2005).

303. Ferraro, P. J., Lawlor, K., Mullan, K. L. & Pattanayak, S. K. Forest Figures: Ecosystem Services Valuation and Policy Evaluation in Developing Countries. *Rev. Environ. Econ. Policy* **6,** 20–44 (2012).

304. Sills, E., Shanley, P., Paumgarten, F., de Beer, J. & Pierce, A. in *Non-Timber For. Prod. Glob. Context* (ed. S. Shackleton et al.) 23–51 (Springer-Verlag Berlin Heidelberg, 2011).

305. Cavendish, W. Empirical regularities in the poverty-environment relationship of rural households: Evidence from Zimbabwe. *World Dev.* **28,** 1979–2003 (2000).

306. Pearce, D. W. The Economic Value of Forest Ecosystems. *Ecosyst. Heal.* **7,** 284–296 (2001).

307. Pearce, D., Putz, F. E. & Vanclay, J. K. Sustainable forestry in the tropics: panacea or folly? *For. Ecol. Manage.* **172,** 229–247 (2003).

308. Ticktin, T. The ecological implications of harvesting. *J. Appl. Ecol.* **41,** 11–21 (2004).

309. Asner, G. P. *et al.* Condition and fate of logged forests in the Brazilian Amazon. *Proc. Natl. Acad. Sci. U. S. A.* **103,** 12947–50 (2006).

310. Belcher, B. & Schreckenberg, K. Commercialisation of Non-timber Forest Products: A Reality Check. *Dev. Policy Rev.* **25,** 355–377 (2007).

311. Moegenburg, S. M. & Levey, D. J. Prospects for conserving biodiversity in Amazonian extractive reserves. *Ecol. Lett.* **5,** 320–324 (2002).

312. Millennium Ecosystem Assessment. *Ecosystems and Human Well-Being: Synthesis*. (Island Press, 2005).

313. Simpson, R. D. *The 'Ecosystem Service Framework': A Critical Assessment*. (UNEP, 2011).

314. Daily, G. C. *et al.* Ecosystem services in decision making: time to deliver. *Front. Ecol. Environ.* **7,** 21–28 (2009).

315. Daily, G. C. & Matson, P. A. Ecosystem services: From theory to implementation. *Proc. Natl. Acad. Sci. U. S. A.* **105,** 9455–9456 (2008).

316. Balmford, A. *et al.* Economic Reasons for Conserving Wild Nature. *Science* **297,** 950–953 (2002).

317. Simpson, R. D. *Allocating Land for An Ecosystem Service: A Simple Model of Nutrient Retention with an Application to the Chesapeake Bay Watershed*. (U.S. Environmental Protection Agency National Center for Environmental Economics, 2010).

318. Ridder, B. Questioning the ecosystem services argument for biodiversity conservation. *Biodivers. Conserv.* **17,** 781–790 (2008).

319. Mascaro, J., Hughes, R. & Schnitzer, S. Novel forests maintain ecosystem processes after the decline of native tree species. *Ecol. Monogr.* **82,** 221–228 (2012).

320. Vilà, M. *et al.* Ecological impacts of invasive alien plants: a meta-analysis of their effects on species, communities and ecosystems. *Ecol. Lett.* **14,** 702–708 (2011).

321. Swift, M., Izac, A. & van Noordwijk, M. Biodiversity and ecosystem services in agricultural landscapes - are we asking the right questions? *Agric. Ecosyst. Environ.* **104,** 113–134 (2004).

322. Cardinale, B. J. *et al.* Biodiversity loss and its impact on humanity. *Nature* **486,** 59–67 (2012).

323. Vellend, M. *et al.* Global meta-analysis reveals no net change in local-scale plant biodiversity over time. *Proc. Natl. Acad. Sci. U. S. A.* **110,** 19456–19459 (2013).

324. Ellis, E. C., Antill, E. C. & Kreft, H. All Is Not Loss: Plant Biodiversity in the Anthropocene. *PLoS One* **7,** e30535 (2012).

325. Sax, D. F. & Gaines, S. D. Species diversity: from global decreases to local increases. *Trends Ecol. Evol.* **18,** 561–566 (2003).

326. Ehrenfeld, D. in *Biodiversity* (ed. E.O. Wilson) 212–216 (National Academy Press, 1988).

327. Fitter, A. H. Are Ecosystem Services Replaceable by Technology? *Environ. Resour. Econ.* **55,** 513–524 (2013).

328. Ghazoul, J. Challenges to the Uptake of the Ecosystem Service Rationale for Conservation. *Conserv. Biol.* **21,** 1651–1652 (2007).

329. Redford, K. H. & Adams, W. M. Payment for Ecosystem Services and the Challenge of Saving Nature. *Conserv. Biol.* **23,** 785–787 (2009).

330. Miles, L. & Kapos, V. Reducing greenhouse gas emissions from deforestation and forest degradation: global land-use implications. *Science* **320,** 1454–5 (2008).

331. Fry, I. Reducing Emissions from Deforestation and Forest Degradation: Opportunities and Pitfalls in Developing a New Legal Regime. *Rev. Eur. Community Int. Environ. Law* **17,** 166–182 (2008).

332. Clements, T. Reduced Expectations: the political and institutional challenges of REDD+. *Oryx* **44,** 309–310 (2010).

333. Simpson, D. in *Handb. Econ. Ecosyst. Serv. Biodivers.* (eds. Nunes, P. A. L. D., Kumar, P. & Dedeurwaerdere, T.) 233–252 (Edward Elgar Publishing Limited, 2014).

334. Carvalheiro, L. G., Seymour, C. L., Veldtman, R. & Nicolson, S. W. Pollination services decline with distance from natural habitat even in biodiversity-rich areas. *J. Appl. Ecol.* **47,** 810–820 (2010).

335. Escobedo, F. J. & Nowak, D. J. Spatial heterogeneity and air pollution removal by an urban forest. *Landsc. Urban Plan.* **90,** 102–110 (2009).

336. Olschewski, R., Tscharntke, T., Benítez, P. C., Schwarze, S. & Klein, A. Economic Evaluation of Pollination Services Comparing Coffee Landscapes in Ecuador and Indonesia. *Ecology and Society* **11,** 7 (2006).

337. Simpson, R. D. Ecosystem services as substitute inputs: Basic results and important implications for conservation policy. *Ecol. Econ.* **98,** 102–108 (2014).

338. Lutz, W., Butz, W. & KC, S. *World Population and Human Capital in the Twenty-First Century.* (Oxford University Press, 2014).

339. Gerland, P. *et al.* World population stabilization unlikely this century. *Science* **346,** 234–237 (2014).

340. Mueller, N. D. *et al.* Closing yield gaps through nutrient and water management. *Nature* **490,** 254–257 (2012).

341. Kastner, T., Erb, K. H. & Haberl, H. Rapid growth in agricultural trade: effects on global area efficiency and the role of management. *Environ. Res. Lett.* **9,** 034015 (2014).

342. Bongiovanni, R. & Lowenberg-Deboer, J. Precision Agriculture and Sustainability. *Precis. Agric.* **5,** 359–387 (2004).

343. Grau, H. R., Gasparri, N. I. & Aide, T. M. Balancing food production and nature conservation in the Neotropical dry forests of northern Argentina. *Glob. Chang. Biol.* **14,** 985–997 (2008).

344. Herrero, M. *et al.* Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proc. Natl. Acad. Sci. U. S. A.* **110,** 20888–20893 (2013).

345. Boserup, E. *The Conditions of Agricultural Growth*. (Aldine Publishing Company, 1965).

346. Denning, G. *et al.* Input Subsidies to Improve Smallholder Maize Productivity in Malawi: Toward an African Green Revolution. *PLoS Biol.* **7,** e1000023 (2009).

347. Fisher, M. & Shively, G. E. Agricultural Subsidies and Forest Pressure in Malawi's Miombo Woodlands. *J. Agric. Resour. Econ.* **32,** 349–362 (2007).

348. Nautiyal, S. & Kaechele, H. Fuel switching from wood to LPG can benefit the environment. *Environ. Impact Assess. Rev.* **28,** 523–532 (2008).

349. McDonald, R. I., Fargione, J., Kiesecker, J., Miller, W. M. & Powell, J. Energy Sprawl or Energy Efficiency: Climate Policy Impacts on Natural Habitat for the United States of America. *PLoS One* **4,** e6802 (2009).

350. Searchinger, T. *et al.* Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change. *Science* **319,** 1238–1240 (2008).

351. Searchinger, T. & Heimlich, R. *Avoiding Bioenergy Competition for Food Crops and Land*. (World Resources Institute, 2015).

352. Lapola, D. M. *et al.* Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proc. Natl. Acad. Sci. U. S. A.* **107,** 3388–3393 (2010).

353. Arima, E. Y., Richards, P., Walker, R. & Caldas, M. M. Statistical confirmation of indirect land use change in the Brazilian Amazon. *Environ. Res. Lett.* **6,** 024010 (2011).

354. Villoria, N. B. & Hertel, T. W. Geography Matters: International Trade Patterns and the Indirect Land Use Effects of Biofuels. *Am. J. Agric. Econ.* **93,** 919–935 (2011).

355. Kim, S. & Dale, B. E. Indirect land use change for biofuels: Testing predictions and improving analytical methodologies. *Biomass and Bioenergy* **35,** 3235–3240 (2011).

356. Seufert, V., Ramankutty, N. & Foley, J. A. Comparing the yields of organic and conventional agriculture. *Nature* **485,** 229–232 (2012).

357. Ponisio, L. C. *et al.* Diversification practices reduce organic to conventional yield gap. *Proc. R. Soc. London B Biol. Sci.* **282,** 20141396 (2015).

358. Aide, T. & Grau, H. Globalization, Migration, and Latin American Ecosystems. *Science* **305,** 1915–1916 (2004).

359. Rigg, J. Land, Farming, Livelihoods, and Poverty: Rethinking the Links in the Rural South. *World Dev.* **34,** 180–202 (2006).

360. Grau, H. R. & Aide, M. Globalization and Land-Use Transitions in Latin America. *Ecol. Soc.* **13,** 16 (2008).

361. Robinson, J. G. & Bennett, E. L. Will alleviating poverty solve the bushmeat crisis? *Oryx* **36,** 332 (2002).

362. Wilkie, D. S. & Godoy, R. A. Income and Price Elasticities of Bushmeat Demand in Lowland Amerindian Societies. *Conserv. Biol.* **15,** 761–769 (2001).

363. Apaza, L. *et al.* Meat prices influence the consumption of wildlife by the Tsimane' Amerindians of Bolivia. *Oryx* **36,** 382–388 (2002).

364. Wilkie, D. S. *et al.* Role of Prices and Wealth in Consumer Demand for Bushmeat in Gabon, Central Africa. *Conserv. Biol.* **19,** 268–274 (2005).

365. Brashares, J. S., Golden, C. D., Weinbaum, K. Z., Barrett, C. B. & Okello, G. V. Economic and geographic drivers of wildlife consumption in rural Africa. *Proc. Natl. Acad. Sci. U. S. A.* **108,** 13931–13936 (2011).

366. DeFries, R. & Pandey, D. Urbanization, the energy ladder and forest transitions in India's emerging economy. *Land use policy* **27,** 130–138 (2010).

367. Crousillat, E., Hamilton, R. & Antmann, P. *Addressing the Electricity Access Gap.* (World Bank, 2010).

368. Portale, E. & de Wit, J. *Tracking Progress Toward Sustainable Energy for All in Sub-Saharan Africa.* (World Bank, 2014).

369. Iiyama, M. *et al.* The potential of agroforestry in the provision of sustainable woodfuel in sub-Saharan Africa. *Curr. Opin. Environ. Sustain.* **6,** 138–147 (2014).

370. Lee, R. The Demographic Transition: Three Centuries of Fundamental Change. *J. Econ. Perspect.* **17,** 167–190 (2003).

371. UNFPA. *State of the world population 2007: Unleashing the potential of urban growth.* (UNFPA, 2007).

372. Huber, J. Pioneer countries and the global diffusion of environmental innovations: Theses from the viewpoint of ecological modernisation theory. *Glob. Environ. Chang.* **18,** 360–367 (2008).

373. Henderson, J. & Kauffman, N. The Wealth Effect in U.S. Agriculture. *Main Str. Econ.* **1,** 1–7 (2013).

374. Smith, R. J., Muir, R. D. J., Walpole, M. J., Balmford, A. & Leader-Williams, N. Governance and the loss of biodiversity. *Nature* **426,** 67–70 (2003).

375. Margules, C. R. & Pressey, R. L. Systematic conservation planning. *Nature* **405,** 243–253 (2000).

376. Kiesecker, J. M., Copeland, H., Pocewicz, A. & McKenney, B. Development by design: blending landscape-level planning with the mitigation hierarchy. *Front. Ecol. Environ.* **8,** 261–266 (2010).

377. Groves, C. R. *et al.* Planning for Biodiversity Conservation: Putting Conservation Science into Practice. *Bioscience* **52,** 499–512 (2002).

378. Lutz, W., Sanderson, W. & Scherbov, S. IIASA's 2007 Probabilistic World Population Projections. *IIASA World Popul. Progr. Online Data Base Results 2008* (2012). at <http://www.iiasa.ac.at/Research/POP/proj07/index.html?sb=5>

379. Aide, T. M. *et al.* Deforestation and Reforestation of Latin America and the Caribbean (2001–2010). *Biotropica* **45,** 262–271 (2013).

380. Chapron, G. *et al.* Recovery of large carnivores in Europe's modern human-dominated landscapes. *Science,* **346,** 1517–1519 (2014).

381. Sloan, S. Fewer People May Not Mean More Forest for Latin American Forest Frontiers. *Biotropica* **39,** 443–446 (2007).

382. Freese, C. H. *et al.* Second chance for the plains bison. *Biol. Conserv.* **136,** 175–184 (2007).

383. Tercek, M. & Adams, J. Nature's Fortune: How Business and Society Thrive by Investing in Nature. (Basic Books, 2013).

384. Ziv, G., Baran, E., Nam, S., Rodríguez-Iturbe, I. & Levin, S. A. Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin. Proc. Natl. Acad. Sci. U. S. A. 109, 5609–5614 (2012).

385. Laurance, W. F. et al. A global strategy for road building. Nature 513, 229–232 (2014).

386. Stevenson, J. R., Villoria, N., Byerlee, D., Kelley, T. & Maredia, M. Green Revolution research saved an estimated 18 to 27 million hectares from being brought into agricultural production. Proc. Natl. Acad. Sci. U. S. A. 110, 8363–8368 (2013).

387. Nakicenovic , N. Freeing Energy from Carbon. Daedalus 125, 95–112 (1996).

388. Foray, D. & Grübler, A. Technology and the Environment: An Overview. Technol. Forecast. Soc. Change 53, 3–13 (1996).

389. Block, F. & Keller, M. R. State of Innovation: The U.S. Government's Role in Technology Development. (Paradigm Publishers, 2011).

390. Gertner, J. The Idea Factory: Bell Labs and the Great Age of American Innovation. (Penguin Books Ltd., 2012).

391. Rosenberg, N. & Steinmueller, W. E. Engineering knowledge. Ind. Corp. Chang. 22, 1129–1158 (2013).

392. Etzkowitz, H., Webster, A., Gebhardt, C. & Terra, B. R. C. The future of the university and the university of the future: evolution of ivory tower to entrepreneurial paradigm. Res. Policy 29, 313–330 (2000).

393. Mazzucato, M. The Entrepreneurial State: Debunking Public vs. Private Myths in Innovation. (Anthem Press, 2013).

394. Ruttan, V. W. Technology, Growth, and Development: An Induced Innovation Perspective. (Oxford University Press, 2001).

395. Cullather, N. The Hungry World: America's Cold War Battle against Poverty in Asia. (Harvard University Press, 2010).

396. Pardey, P. G., Chan-Kang, C., Beddow, J. & Dehmer, S. Long-run and Global R&D Funding Trajectories: The US Farm Bill in a Changing Context. in 2015 Allied Soc. Sci. Assoc. Annu. Meet. January 3-5, 2015, Boston, Massachusetts (2014).

397. Kemp, R. & Pontoglio, S. The innovation effects of environmental policy instruments - A typical case of the blind men and the elephant? Ecol. Econ. 72, 28–36 (2011).

398. Vollebergh, H. R. J. Impacts of Environmental Policy Instruments on Technological Change. (OECD, 2007).

399. Calel, R. & Dechezleprêtre, A. Environmental Policy and Directed Technological Change: Evidence from the European Carbon Market. Rev. Econ. Stat. doi:10.1162/REST_a_00470 (2014).

400. Marvier, M., McCreedy, C., Regetz, J. & Kareiva, P. A Meta-Analysis of Effects of Bt Cotton and Maize on Nontarget Invertebrates. Science 316, 1475–1477 (2007).

401. Bruckner, T. et al. in Clim. Chang. 2014 Mitig. Clim. Chang. Contrib. Work. Gr. III to Fifth Assess. Rep. Intergov. Panel Clim. Chang. (eds. Edenhoger, O. et al.) 511–598 (Cambridge University Press, 2014).

402. Kavanagh, M. Buffett Foundation Funds Hydro Plan in Congo Gorilla Park. Bloomberg (2013). at <http://www.bloomberg.com/news/articles/2013-05-03/buffett-foundation-funds-hydro-plan-in-congo-gorilla-park>

403. The Nature Conservancy. Smart Development. (2015). at <http://www.nature.org/ourinitiatives/urgentissues/smart-development>

BREAKTHROUGH INSTITUTE

436 14TH STREET, SUITE 820, OAKLAND, CA 94612
PHONE: 510-550-8800 〉WEBSITE: WWW.THEBREAKTHROUGH.ORG