CHAPTER 3

Biodiversity and the Economic Value of Species Abundance

"Like winds and sunsets, wild things were taken for granted until progress began to do away with them."

—*Aldo Leopold*, American writer and scientist (1887–1948)

Key messages

- Biodiversity is in crisis, with all major indicators showing rapid declines. This matters for development because biodiversity affects ecosystems that in turn have economic impacts.
- Information on the linkages between biodiversity and the economy is limited. Nevertheless, a rapidly growing empirical literature provides invaluable insights and identifies three major pathways through which impacts are channeled:
  - The introduction or removal of a single species can have wide-reaching—and often unforeseen—economic consequences. Interactions between species are complex, but new data have been helpful in revealing impacts on the economy, which can be surprisingly significant.
  - The diversity and abundance of species are crucial determinants of the productivity and resilience of ecosystem services, affecting everything from agricultural yields, to soil moisture and water purification.
  - Ecosystems regulate temperature, rainfall, nutrient recycling, water flows, and other environmental conditions. Disruptions to these regulatory functions can have substantial economic impacts.
- Countries can use various approaches to reverse the decline of ecosystems, from payments for ecosystem services, to conservation tenders, to protected areas, and collaborative management partnerships. There is no policy panacea, although well-designed policies that are mindful of incentives have been more successful than blunt regulations.

Introduction

The Indian peacock, with its iridescent plumage and extravagant tail feathers, stands out as one of the most beautiful birds on Earth. In stark contrast, the vulture, with its unkempt appearance and scavenging habits, may never be celebrated for its beauty or grace. Yet the vulture plays a pivotal economic role, far beyond its unassuming looks. A path-breaking study by Frank and Sudarshan (2024), in the prestigious *American Economic Review*, tracked a hidden link between the collapse of vulture populations in South Asia and the resulting economic damages, estimated at a staggering $69 billion annually. Vultures feed primarily on the carcasses of dead animals and are equipped with stomach acids that neutralize harmful bacteria and toxins. Their disappearance left a void, leading to rotting carcasses that became breeding grounds and vectors for infectious diseases like rabies and anthrax, costing billions in mortality and morbidity.

As this example highlights, biodiversity loss often has unpredictable effects and is typically irreversible. Ecosystems are highly complex, with species interconnected through a web of relationships such as predation, competition, and symbiosis. The loss of a single species in a food web can cascade through an ecosystem with surprising economic consequences as the example of the loss of vultures illustrates.[1] Habitat loss and fragmentation are the main causes of biodiversity loss. The size of habitat patches and their connectivity are crucial. As smaller patches are created, the diversity within them declines. Recent assessments have suggested that the ecosystem services provided by biodiversity, such as the capacity to pollinate crops, regulate pests, and limit soil erosion, decline significantly when a habitat area falls below 20–25 percent per square kilometer (Mohamed et al. 2024). This chapter highlights recent empirical research that has unveiled some of the unseen dependencies and economic consequences.

Biodiversity is in crisis and in the midst of a "mass extinction" (McCallum 2015). Approximately 75 percent of the world's land surface has been significantly altered by humanity, 70 percent of monitored wildlife has vanished in the past 40 years, and 60 percent of global extinctions have been influenced by the introduction of invasive alien species (IPBES 2019, 2023). Of all the mammalian biomass on Earth today, wild mammals comprise a mere 5 percent—the remaining 95 percent consists of humans (35 percent) and mammals for human consumption (60 percent). Such is the impact of the anthropogenic forces that drive this decline, much of which is due to habitat loss driven by the agriculture, forestry, and mining sectors (McElwee et al. 2024).

Despite the magnitude of these shifts, understanding of the economic consequences is limited. The term biodiversity was coined but half a century ago (Wilson and Peter 1988) and is only now beginning to capture policy attention. In general, the costs of species extinction are hard to estimate as there is a scarcity of comprehensive data

linking ecosystems to their economic impacts. Most available information tends to focus on marginal changes in ecosystems, which limits understanding of the consequences of large collapses. In addition, establishing causal relationships is challenging due to the lack of extensive data on species population counts.

Estimates based on accounting approaches suggest that more than half of the world's total gross domestic product is "moderately or highly dependent" on nature and its services (World Economic Forum 2020). New research by S&P has indicated that 85 percent of the world's largest companies that make up the S&P Global 1200 Index have a significant dependency on nature and biodiversity across their direct operations (S&P Global 2023). The consequences of biodiversity loss also reverberate through financial markets—albeit to a more limited extent (Cherief, Sekine, and Stagnol 2025; Giglio et al. 2024). There have also been heroic efforts to model the macroeconomic impacts of biodiversity losses (for example, Costanza et al. 1997; Johnson et al. 2021). However, in the absence of sufficient information on the way biodiversity connects with the economy, or data on the magnitude involved, and the functional form of these interactions, such efforts remain informative but incomplete. As a result, there are more unknowns than knowns in this nascent field of research.

This chapter delves into new and groundbreaking empirical research on the interaction between the economy and biodiversity. At least three pathways have been identified in recent research on how biodiversity and ecosystems exert economic impacts. First, species within a food web are interconnected, implying that alterations in species composition can trigger chain reactions—known as trophic cascades. The literature has suggested that these can have significant, although often elusive, economic consequences. These are among the most complex and least understood issues in environmental economics. Second, the diversity and abundance of species are crucial determinants of the productivity and resilience of ecosystem services, affecting everything from agricultural yields to soil moisture and water purification. Third, well-functioning ecosystems can regulate temperature, evapotranspiration, nutrient recycling, water flows, and other environmental conditions. Disruptions to these regulatory functions can have substantial economic repercussions. A better understanding of these pathways is critical to improving economic efficiency and policy effectiveness.

Species interactions

To a large degree, ecosystems are shaped and defined by the way species interact, which affects the flow of nutrients and energy (Estes et al. 2011). Species interactions can be direct or indirect. The former include predator-prey relationships, competition over resources, and provision of mutual benefits. *Trophic cascades* describe situations where population changes in one part of the food web directly or indirectly affect the abundance and behavior of species in another part of the web. These can be *top-down*

cascades, such as the predatory pressure on herbivores changing the abundance of vegetation, or *bottom-up cascades*, such as a decline in plankton narrowing the food base and resulting in lower fish population levels further up the food chain. Indirect interactions can also occur when species change the environment by affecting the flow of water or impacting the microclimate, which then impacts other species.

The stabilizing role of biodiversity in an ecosystem can deteriorate well before any species becomes locally extinct. Depleted population levels of species can result in "functional extinctions" and the rapid degradation of ecosystem services (Valiente-Banuet et al. 2014). Although the thresholds for these tipping points where species experience a collapse in their ability to perform their function are hard to quantify, they are recognized as vital to understanding how biodiversity losses can affect human well-being (Díaz et al. 2006). This is particularly so when considering species that have an effect on the ecosystem that is disproportionate to their abundance (Power et al. 1996).

This section considers the economic impacts of three types of species interaction: predation, biological pest control, and damage from invasive species.

Economic implications of predation

Top-down control of herbivores can dramatically alter ecosystems, with impacts ranging from flood risk to pest control. An iconic and much debated example is the reintroduction of gray wolves into Yellowstone National Park in the United States (Beschta and Ripple 2006, 2019). Their return reduced browsing by herbivores on vegetation by up to 80 percent (Ripple and Beschta 2003, 2012), leading to cascading impacts from vegetation recovery and the return of beavers, and even altered river flows (Allen et al. 2017; Mech 2017). Beavers thrive in habitats created by more robust willow growth, which in turn depends on reduced herbivory (consumption of plant material). Analysis has shown that willow regeneration is better explained by browsing pressures than by climate shifts (Ripple and Beschta 2006).

Although debate remains over the precise causal chain in Yellowstone, the broader pattern of trophic cascades has been well-established. As presented in chapter 2 of this report, trophic cascades can have significant impacts on water regulation services, enhancing soil moisture regulation and buffering the impacts of droughts—benefits with clear economic value.

Biodiversity's contributions can often manifest in unexpected places. The recolonization of wolves in Wisconsin, United States, has been linked to a 23.7 percent drop in deer-vehicle collisions due to behavioral shifts in deer prompted by the "ecology of fear" (Raynor, Grainger, and Parker 2021). Similar effects have been observed in Quebec, Canada, where wolf presence correlates with fewer animal-related traffic accidents (Frank, Missiran, et al. 2024). Wolves and other large predators often hunt near roads or trails, pushing deer away from these high-risk areas (Ripple and Beschta 2004).

Predation also benefits aquatic environments. In coastal regions, sea otters help restore wetlands by controlling crab populations, which overgraze marsh vegetation. This predation improves plant biomass and soil stability (Dedman et al. 2024; Heithaus et al. 2014; Hughes et al. 2024).

Economic implications of biological pest control

Trophic interactions foster a balanced and diverse assemblage of species, which in turn may provide natural pest control services and promote ecosystem stability. However, despite growing evidence of the scale of beneficial services provided through natural pest control, the importance of biological pest control remains largely underappreciated until damage becomes visible.

The extent of damage resulting from the loss of biological pest control services usually becomes apparent only when the harmful effects manifest in tangible losses. In South Asia the use of the painkiller diclofenac to treat cattle proved lethal to vultures, causing their sudden collapse. As noted in the Introduction to this chapter, the collapse of the vulture population resulted in the loss of sanitation services. This culminated in diseases such as anthrax and $69.4 billion in health damages (Frank and Sudarshan 2024).

In another prominent example, the eradication of sparrows in China was a component of the "Four Pests Campaign" launched in 1958, which aimed to eliminate rats, flies, mosquitoes, and sparrows. Sparrows were targeted because they were believed to consume significant quantities of grain. However, the campaign failed to recognize the crucial ecological role that sparrows played in controlling insect populations. The large-scale reduction of sparrow populations led to an insect population boom, which exacerbated crop damage and contributed to significant agricultural losses. This ecological imbalance is considered one of the factors that worsened the Great Chinese Famine (Frank, Wang, et al. 2024).

In the absence of effective biological pest control, farmers are often compelled to increase insecticide applications, with consequences for surrounding communities. Investigating the expansion of a bat-killing wildlife disease known as white-nose syndrome, novel research documented that as local bat populations perished, farmers compensated for the decline in pest control services with higher insecticide use (31 percent), which generated negative health impacts in the form of elevated infant mortality rates (7.9 percent) (Frank 2024). Perhaps more surprisingly, the expansion of this bat disease and the resulting reduction in biological pest control also caused a decline in agricultural rental land values (Manning and Ando 2022).

Economic implications of invasive species

Introducing new species into an ecosystem with no natural population controls can lead to large fluctuations in ecosystem functioning. Such introductions are called

non-native species. When they cause sharp, observable changes, they are considered invasive species. All invasive species are non-native, but many non-native species cause little or no meaningful impact.

In 2023, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services conducted a thematic assessment of invasive alien species. The assessment estimated that damages have "quadrupled every decade since 1970" and cost roughly $423 billion a year (IPBES 2023). Scientists warn about the projected growth in the number of invasive species due to increased international trade, land use change, climate change, and inadequate prevention and control measures (Paini et al. 2016; Pyšek et al. 2020). Quantifying the full scope of damages from all invasive species is challenging; however, estimates for the United States suggest that the damages are more than $100 billion a year (Pimentel et al. 2000; Pimentel, Zuniga, and Morrison 2005; Shwiff et al. 2018).[2] Among other channels, invasive species spread through trade networks (Chapman et al. 2017), exacerbated by the burgeoning demand for exotic plants and wild animals as pets—some of which are illegal (Harrison, Roberts, and Hernandez-Castro 2016; Humair et al. 2015).

Productivity, resilience, and household incomes

A longstanding hypothesis in ecology is that more diverse ecosystems are more productive. A seminal experiment by Tilman, Wedin, and Knops (1996) showed that grassland plots with higher plant diversity have higher productivity. Subsequent analysis has shown that more diverse grassland plots have higher levels of stability or resilience, measured as lower volatility in productivity (Tilman, Reich, and Knops 2006). These two observed relationships are referred to as the *diversity-productivity* and *diversity-stability hypotheses*.[3]

The diversity-productivity and diversity-stability relationships can have significant beneficial economic impacts, which are gradually being investigated. One conclusion ecologists have drawn from the impacts of higher plant diversity is that agricultural systems might be able to increase their yields and reduce year-on-year variation in yields if they reduce their reliance on monoculture plots and plant more diverse plots. This follows from an observed positive correlation between crop diversity and agricultural productivity (Bareille and Dupraz 2020). Research comparing monoculture plots with more diverse plots found that, on average, high-diversity plots outperformed even the most successful monoculture plots in terms of biomass gain in the long run (Tilman et al. 2001). One potential explanation lies in different plant species having different optimal environmental conditions, allowing more diverse plots to fill gaps left open in less diverse ones (Tilman, Lehman, and Thomson 1997). Similarly, chapter 2 demonstrated that natural—and therefore more diverse—forests can buffer the effects of drought, whereas monoculture forest plantations aggravate drought impacts by absorbing more soil moisture when it is most needed for crops.

A large literature has documented the role that forests play as nature's safety net in times of crisis. For example, analysis of data from 23 countries found that rural households compensated for declining incomes due to droughts by increasing extraction from nearby forests by 30 percent (Noack, Riekhof, and Di Falco 2019). More diverse forests buffered larger shares of the negative income shock. A forest that was more diverse (by one standard deviation) could fully offset the reduction in crop income after a drought. This robust finding emerged from different geographies across developing countries.

Productivity can decline even without a change in species diversity, particularly when the distribution and abundance of key species are affected. For instance, in marine ecosystems, plankton are crucial for food webs and a decline in their populations can lead to reduced biomass in higher trophic levels (box 3.1 discusses the broader crisis in ocean ecosystems, including the impacts of pollution, ocean acidification, and overfishing). A study in Japan highlighted that increased use of neonicotinoids has led to an 83 percent decline in zooplankton biomass, resulting in significant drops in smelt and eel yields by 91 and 74 percent, respectively (Yamamuro et al. 2019). In coastal areas, mangroves play a vital role in supporting fish habitats, and research in Indonesia has revealed a fishery income–mangrove elasticity of 5.3–9.8 percent (Yamamoto 2023). The study indicated that households facing income losses from mangrove decline cut back on nonfood consumption and increased labor in other sectors, yet continued to fish despite reduced returns. Protecting mangrove resources has proved economically beneficial, with the mangrove-fishery link valued at $12,364 to $22,861 per hectare annually, compared to $7,610 for aquaculture and $9,630 for palm plantations (Yamamoto 2023).

BOX 3.1

The dismal state of the ocean

Ocean covers over 70 percent of the Earth's surface and is crucial for climate regulation, food supply, and biodiversity. Despite this, the state of the ocean in 2025 is marked by challenges like pollution, changing chemistry, and overfishing beyond economically and ecologically desirable limits.

- *Pollution.* Plastic waste has continued to rise, with 2 million metric tons entering the oceans annually via rivers (OECD 2022). Most plastic remains near coastal areas, posing threats to marine life and human health (Leslie and Depledge 2020; Street et al. 2024) (map B3.1.1). Nutrient pollution from runoff creates dead zones, depleting oxygen and harming marine life (Breitburg et al. 2018). Even in developed countries this leads to large economic losses, often exceeding $2.4 billion annually in some subregions (Boehm 2020).
- *Changing ocean chemistry.* The ocean absorbs carbon dioxide and becomes more acidic, which affects calcifying organisms like corals and mollusks (Guinotte and Fabry 2008;

(continued)

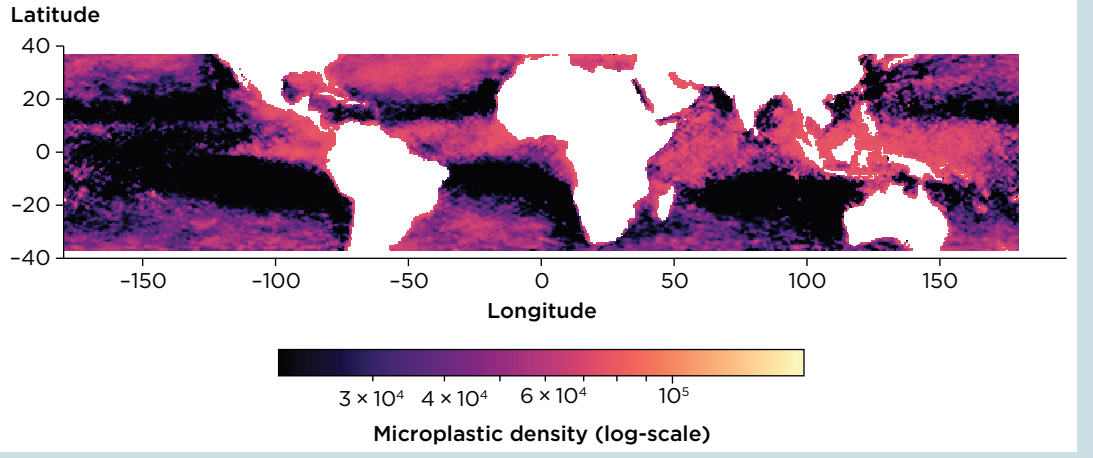
BOX 3.1

The dismal state of the ocean *(continued)*

Hoegh-Guldberg et al. 2014). This disrupts marine ecosystems and food webs. Coral reefs face bleaching from rising temperatures and acidification, with significant losses in the Great Barrier Reef (Bozec et al. 2022). Data platforms can aid reef health by monitoring environmental indicators and providing early warnings.

- *Ocean salinity.* Rising temperatures intensify the hydrological cycle, altering salinity levels and affecting coastal communities that are reliant on fisheries and agriculture (Akhter et al. 2021; Bricheno, Wolf, and Sun 2021; Dasgupta, Wheeler, and Ghosh 2022).
- *Overfishing.* Overfishing depletes fish stocks, with 38 percent harvested unsustainably (FAO 2024). Subsidies and illegal fishing worsen the depletion, although satellite technology aids enforcement. Some improvements have been noted since 2004, but challenges have persisted in balancing exploitation with conservation.

MAP B3.1.1 Global ocean plastic density (mean, 2017–18)



Source: Original calculation based on CYGNSS 2021.
Note: The latitude restriction in the map is due to the data source.

Marine protected areas (MPAs) remain the cornerstone of efforts to mitigate damage to ocean fisheries. MPAs aim to protect 30 percent of the ocean by 2030, offering benefits for fish stocks and ecosystems (from the 15th meeting of the Conference of the Parties to the United Nations Convention on Biological Diversity). Studies have shown that MPAs enhance fish biomass and coral reef resilience (Carassou 2013; Gill et al. 2017). Socioeconomic impacts vary, with successful outcomes linked to no-take, well-enforced, and older MPAs (Ban et al. 2019). Effective MPAs boost local economies and fisheries, although some have faced resistance due to access restrictions (Christie 2004; Weigel et al. 2015). Co-management MPAs, which often involve shared responsibilities among governments, communities, and nongovernmental organizations, have shown to balance ecological and socioeconomic goals, improving governance and compliance (Barley Kincaid, Rose, and Mahudi 2014).

Pollination is a crucial ecological process that is vital for the reproduction of many flowering plants, which in turn provide food and habitat. In addition, approximately 75 percent of the world's food crops depend on animal pollinators, making pollination essential for global food security (Klein et al. 2007). The decline in pollinator populations due to habitat loss, pesticide use, and climate change poses risks to biodiversity and agriculture. Several studies have suggested that the decline of pollinators has led to large economic losses. However, causality is difficult to establish and most work has relied on correlations between pollinator presence and crop yields.

Ambient environmental quality

Well-functioning ecosystems can regulate temperature, evapotranspiration, nutrient recycling, water flows, and other environmental conditions. Disruptions to these regulatory functions can increase air pollution levels and the likelihood of flooding and reduce productivity and land values, leading to the loss of environmental amenities (Berryman 1989; van Breugel et al. 2024). One such example is deforestation in the Amazon region, which has altered regional rainfall patterns, which, in turn, impact agricultural productivity, hydropower generation, and economic performance in affected areas (chapter 2). Linkages have been observed across multiple ecosystems, affecting freshwater, air quality, and temperature (Brockerhoff et al. 2017; D'Odorico et al. 2013; De Frenne et al. 2013; McLaughlin and Cohen 2013; Zellweger et al. 2020).

Trees provide a vast array of nontimber ecosystem services, from regulating temperatures to reducing local pollution, and recent evidence indicates that forested areas boost worker productivity by moderating ambient temperatures. For example, a study in Indonesia that randomly assigned workers to forested and deforested settings revealed a 2.84-degree Celsius difference in wet-bulb temperature[4] and an 8.22-percent decrease in productivity in the hotter, deforested areas (Masuda et al. 2021). Cognitive performance is also worse in deforested settings (Masuda et al. 2020). Another study linked the loss of tree cover due to the emerald ash borer in the United States to a 2.1 percentage point increase in the probability of a relatively hot day, above 32.2 degrees Celsius (Jones 2019). A vast literature has documented the temperature-regulating effects of tree cover in urban areas (refer to chapter 6). For example, research in Toronto, Canada, found that summer month temperatures in neighborhoods with higher tree cover are 0.8 degree Celsius lower, alleviating energy demand for cooling (Han et al. 2024).

Forests also regulate local microclimates, and their impacts extend far downwind or downstream. For example, temperature and precipitation regulation effects from the Great Plains Shelterbelt, a 1930 forestation program in the Midwestern United States, extend 200 kilometers downwind, and counties with high exposure to the shelterbelt have experienced, on average, precipitation that is 3 percent higher and summer-time maximum

temperatures that are 0.9 percent lower, boosting corn production by 30 percent (Grosset-Touba, Papp, and Taylor 2024). By lowering the likelihood of crop failure, such changes in environmental conditions also slow down the process of farm consolidation. As noted in chapter 2, intact forests help mitigate drought effects and increase precipitation when winds pass over tropical rainforests, enhancing resilience against dry conditions and delivering essential rainfall for agriculture and hydropower downstream.

Intact forests improve human health by controlling disease vectors and reducing waterborne diseases. In Indonesia, a 1 percent decline in forest cover was linked to a 10 percent rise in malaria cases (Garg 2019). This association was impacted by the biodiversity of forests, with less diverse ecosystems showing stronger links to malaria due to the loss of mosquito predators. Another study found that a 1 percent decline in forest cover increased the probability of childhood diarrheal disease by 5.8 percent and stunting by 3.9 percent due to diminished water quality further downstream (Damania et al. 2024). However, in contrast, a study in China found mixed results from urban afforestation: although air quality improved, hospital visits for allergies increased due to a rise in pollen (Xing et al. 2023).

Reversing the decline of ecosystems

Ecosystem intactness is vital for maintaining natural balance and providing essential services that are crucial for human and economic well-being. Disruptions lead to negative effects on biodiversity and society. Restoring and preserving ecosystems is key to resilience and sustainability. Ecosystem restoration involves activities aimed at recovering ecosystem health and sustainability. Cost-effective forest restoration is achievable, at an estimated $1,382 per hectare, and the most affordable restoration areas are in Latin America and Sub-Saharan Africa (Herrera Garcia, Vincent, and Chang 2024). Common approaches to restoring or conserving ecosystems include the following:

Payment for ecosystem services (PES). PES schemes offer financial incentives to landowners for maintaining or enhancing ecosystem services (Mirzabaev and Wuepper 2023). However, they often face challenges like adverse selection, where payments are made to those already conserving, reducing additional impact. To improve effectiveness, PES programs could incorporate better targeting and monitoring to ensure that payments lead to genuine conservation actions.

Conservation tenders and auctions. These approaches create competition among environmental service providers, aligning private incentives with public conservation goals. By inviting bids for conservation contracts, tenders can achieve better outcomes at lower costs compared to fixed-price schemes. This method is especially effective in regions with well-defined property rights (Bardsley and Burfurd 2009; James, Lundberg, and Sills 2021).

Biodiversity credits. Biodiversity credits involve trading conservation efforts for credits, which can be purchased by entities looking to enhance their biodiversity footprint. Unlike offsets, which compensate for negative impacts, credits focus on proactive conservation. This market-based approach encourages investment in projects that positively impact biodiversity.

Sustainability-linked bonds. These bonds are designed to channel resources into conservation projects, often backed by public finance to attract private investors. They face challenges due to the nonmonetizable nature of biodiversity benefits, making them less profitable. However, they hold potential for funding large-scale restoration efforts if supported by government subsidies or guarantees (Flammer, Giroux, and Heal 2025).

Protected areas and collaborative approaches. Protected areas aim to conserve biodiversity but are often placed where they cause minimal conflict with economic interests, limiting effectiveness. Collaborative management partnerships between state and nonstate actors can leverage resources and expertise, leading to significant conservation gains, such as reduced deforestation and increased biodiversity (Denny, Englander, and Hunnicutt 2024; Desbureaux et al. 2024).

Infrastructure siting. Infrastructure projects like roads and dams can have extensive ecological impacts, often leading to deforestation and habitat loss far beyond the immediate area. Careful planning is essential to avoid ecologically sensitive areas, as the effects of infrastructure extend as far as 50 kilometers (AIIB 2023). Renewable energy projects should be located on already degraded lands to minimize disruptions. This strategic approach helps preserve biodiversity while still allowing for necessary development.

Monitoring biodiversity. Advances in remote sensing technologies, such as drones and satellite imagery, are crucial for real-time monitoring of ecosystems. They provide data to detect habitat loss and assess the effectiveness of conservation efforts. However, data gaps, especially in remote regions, highlight the need for investment in observation technologies and local capacity building (box 3.2).

BOX 3.2

Earth observation of the Amazon

Famed for its biodiversity, the Amazon faces severe deforestation threats, primarily driven by human activities such as agriculture, logging, and mining. Large-scale cattle ranching and soybean farming have led to the clearing of large areas, while illegal logging strips the forest of valuable timber. Infrastructure projects, such as road building, further fragment the ecosystem, opening it up to even more exploitation. This loss of forest disrupts critical biodiversity, endangering countless species and Indigenous communities that rely on the forest for their survival.

(continued)

BOX 3.2
Earth observation of the Amazon *(continued)*

To combat these challenges, digital technologies are pivotal in enhancing environmental monitoring and supporting climate adaptation. Key requirements include reliable internet connectivity, strong data governance, and active local community involvement with digital skills. Connectivity is crucial but challenging in the Amazon due to its geography. Efforts like Brazil's Infovia project and Peru's National Telecommunications Program aim to improve access by laying fiber-optic cables in riverbeds to connect remote areas (Ministério das Comunicações 2025).

Technologies such as the US National Aeronautics and Space Administration's Landsat satellites and drones provide critical real-time data on forest changes, aiding in the detection of deforestation and illegal activities. These tools enhance enforcement of environmental laws and support sustainable management by providing precise data for conservation efforts. Remote sensors can monitor deforestation and track the carbon cycle without direct interaction with the forest. Digital financial services, where accessible, can support conservation efforts and sustainable economic activities by enabling efficient financial transactions, such as in payment-for-ecosystem services programs. This supports eco-friendly farming and reduces reliance on deforestation-driven industries.

Conclusion

Empirical evidence is increasingly revealing the vital roles that species play in production functions that contribute to human welfare. However, further research is needed as the evidence remains fragmentary. Much of the robust quantifiable research has been conducted in high-income countries, primarily due to better data availability, highlighting a knowledge gap in developing countries, although measurement and data collection are improving. The World Bank Group's Global Biodiversity Species Global Grid database is one initiative addressing this gap by providing spatially disaggregated occurrence data for more than 600,000 species (box 3.3).

BOX 3.3
Global Biodiversity Species Global Grid database

Limited access to up-to-date data, especially in developing regions, has hindered conservation efforts and quantitative analysis. Traditional metrics focus mainly on vertebrates, while emerging threats outpace slow data updates.

To address this gap, Dasgupta, Blankespoor, and Wheeler (2024) used species occurrence records by the Global Biodiversity Information Facility (GBIF) to reassess the spatial distribution of global biodiversity. GBIF's network includes more than 2 million species occurrences, with around 1.3 million new records added over the past two years. Most records include location data, enabling improved spatial estimates for under-mapped species and refining maps for those with existing data.
The study developed an algorithm that generates species maps directly from GBIF data, updating

(continued)

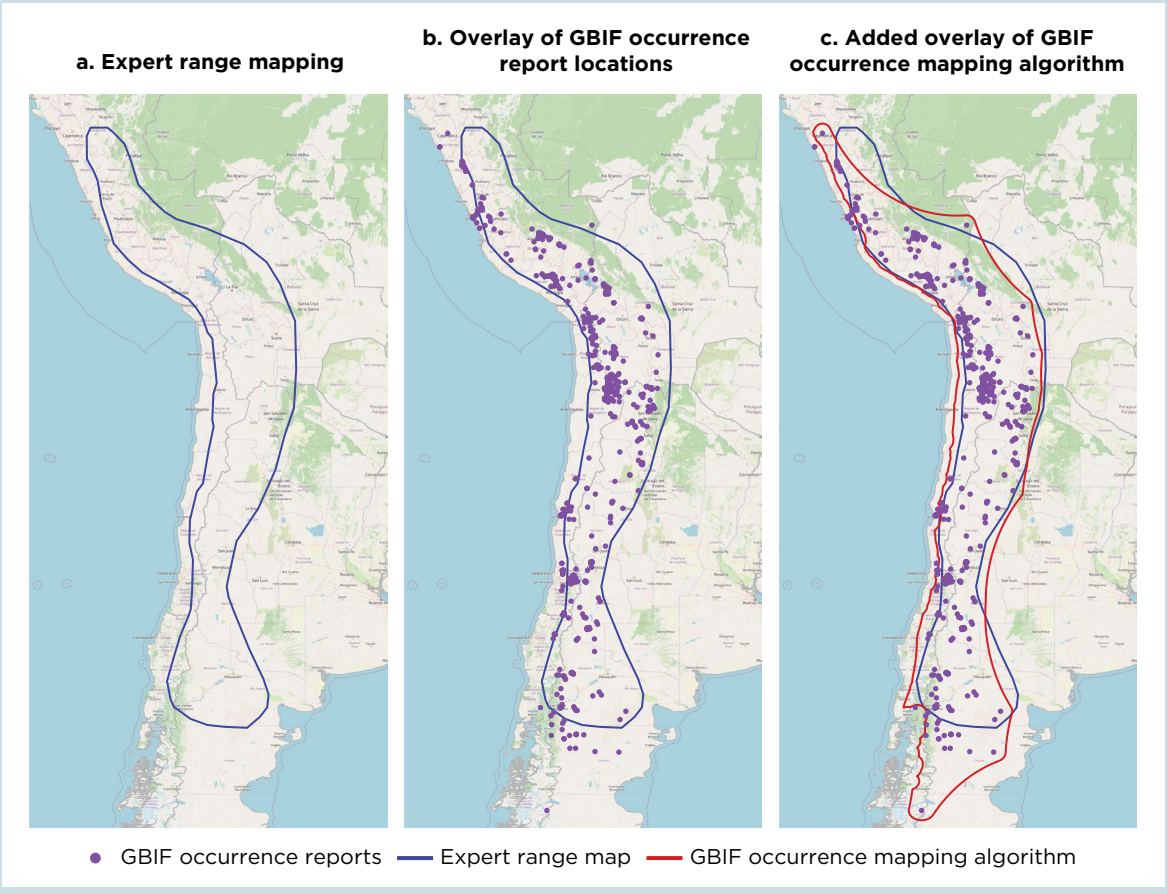
BOX 3.3

Global Biodiversity Species Global Grid database *(continued)*

automatically as new occurrences are added. Maps are produced for around 600,000 species that meet the computational criteria, encompassing a broad range of species, including not only vertebrates, but also invertebrates, plants, fungi, and nonanimal/non-plant species.

For validation, the maps are compared with expert-verified datasets for mammals (Marsh et al. 2022), ants (Kass et al. 2022), and vascular plants (Borgelt et al. 2022). The maps have been found to be in close agreement with global distribution patterns, with regional differences reflecting technical variations or necessary updates to expert maps based on GBIF data. Map B3.3.1 illustrates the spatial distribution of the mountain viscacha in Latin America.

MAP B3.3.1 Mapping exercise results for *Lagidium viscacia* (mountain viscacha), showing overlapping boundaries



Sources: Dasgupta, Blankespoor, and Wheeler 2024; expert range mapping (panel a) based on Burgin et al. 2020.
Note: GBIF = Global Biodiversity Information Facility.

The GBIF's expanding global species database is a valuable resource for conservation. The estimation algorithms have been designed for rapid updates, supporting the ongoing growth of open-source GBIF reports and enabling broader applications in biodiversity conservation.

Notes

1. Biodiversity is categorized into genetic, species, and ecosystem diversity. Genetic diversity refers to the variations in genes within a species, and ecosystem diversity defines the range of different habitats and ecological processes within a given area. Within these categories, alpha biodiversity refers to the diversity within a particular area or ecosystem, typically measured by the number of species in that location. In contrast, beta biodiversity measures the difference in species diversity between ecosystems. Gamma biodiversity refers to the overall diversity of species across a larger geographic area, encompassing multiple ecosystems and combining both alpha and beta diversity.
2. Refer to https://www.nifa.usda.gov/grants/programs/invasive-species-program.
3. Criticism in the literature about these two hypotheses has often focused on the lack of well-understood causal mechanisms and that grassland experiments tend to plant fewer non-native and rare species relative to their presence and abundance in real-world conditions (Dee et al. 2023).
4. This is a measure of temperature that incorporates air temperature and humidity, thus accounting for how well the human body can cool itself via perspiration.

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