Can Countries Expand Agriculture without Losing Biodiversity?

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Weighing the options for feeding a growing world.

Agriculture is leaving a profound footprint on the Earth. With field surveys and modeling techniques, researchers are exploring how to make agricultural landscapes less threatening to biodiversity. In Bokito, Cameroon, a forest transitions to farmland. Photograph: Mokhamad Edliadi/CIFOR.

In Andhra Pradesh, India, Iris Berger removes her shoes before wading into a rice paddy. As water sloshes around her knees, she keeps a wary eye out for the occasional cobra. But mostly, Berger's eyes and ears are fixed on other creatures: birds.

Andhra Pradesh, a state in the country's southeast, is in the middle of a major agricultural shift to using locally sourced inputs rather than chemical pesticides and fertilizers. The hope is that the practice, known as *zero budget natural farming* (ZBNF), will be easier on the farmers' budgets and also on the region's natural resources and wildlife.

Berger, a conservation scientist working on her PhD at the University of Cambridge, is surveying birds on farms and natural areas to learn

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whether ZBNF could prove one solution to a problem researchers and farmers are contending with the world over: how to increase food production without losing biodiversity.

The Earth's biodiversity is in steep decline. Between 1970 and 2016, populations of bird, reptile, mammal, fish, and amphibian species fell an average of 68%, according to the World Wildlife Fund's *Living Planet Report 2020*. The biggest driver threatening endangered species is often habitat loss, says Christopher Crawford, a PhD candidate in the Science, Technology, and Environmental Policy Program in Princeton University's School of Public and International Affairs. "Usually, the biggest driver of habitat loss is land-use change. And usually, that is coming from agriculture."

But the need for food grows. Accounting for changes in climate, global food demand could increase between 30% and 62% from 2010 to 2050, according to a meta-analysis by Michiel van Dijk, of Wageningen Economic Research in the Netherlands, and colleagues in a July 2021 *Nature Food* issue.

Faced with this challenge, Crawford, Berger, and others are using on-the-ground surveys and sophisticated models to strategize about where it is best to farm and where it is best to let nature be. The work points to ways forward—for example, focusing on which uncultivated regions are species poor but could yield good crops and which crops, with improved farming strategies, could produce enough on existing farms. But the work also raises questions, from how to engage policymakers to what the definition of *biodiversity* really is.

In Brazil, a smallholder farmer harvests oil palm. Photograph: Miguel Pinheiro/CIFOR.

Advancing agriculture, retreating species

Agriculture has left a profound imprint. Around 38% of the Earth's land surface is now covered by cropland or livestock grazing areas, according to the Food and Agriculture Organization of the United Nations (FAO).

In a May 2021 study in *Nature Communications*, Karina Winkler, of Wageningen University and Research in the Netherlands, and colleagues estimated that the global agricultural land area increased by around 2 million square kilometers between 1960 and 2019 alone. A January 2022 study in *Nature Food* by the University of Maryland's Peter Potapov and others found that the annual rate of global cropland expansion has nearly doubled over the past two decades.

As farms expand, wilderness retreats. Nearly 90% of global deforestation between 2000 and 2018 occurred because of the expansion of cropland and livestock grazing areas, according to the FAO. In a December 2020 report in *Nature Sustainability*, David Williams, of the University of Leeds, in the United Kingdom, and colleagues identified 1280 vertebrate species projected to lose a quarter or more of their habitat to agricultural expansion by the year 2050 if policy changes fail to make food production less costly to biodiversity.

This biodiversity loss presents an issue, not only for the environment but for farming, because many crops depend on ecosystem services that require biodiversity. Agricultural intensification reduces the abundance and diversity of pollinators and the natural enemies of agricultural pests, explains ecologist Matteo Dainese, of Eurac Research's Institute for Alpine Environment, in Italy.

In 2019, Dainese, then at the University of Würzburg in Germany, and colleagues published a study in *Science Advances* that compiled data on pollinator and pest control species, as well as evidence of pollination and pest control services, from 89 previously published studies covering 1475 agricultural fields across the globe. They found that, as agricultural area around a particular field increased, species richness—the numbers of species providing pollination and pest control services to the field—declined. Successful pollination and pest control depended not only on a species's overall abundance but also on this species's richness. In fact, greater agricultural expansion around a field indirectly resulted in lower yields because of the decrease in the number of species. "It is important to maintain biodiversity," says Dainese.

Foreseeing crop expansion

To protect biodiversity, it helps to know which land is likely to be cleared next—and for what cause. Maybe a new soybean field is an isolated development. Or maybe it is the start of a farming trend that could

In Borneo, natural habitat is being logged to make way for oil palm. Photographs: L. Roman Carrasco/National University of Singapore.

sweep into neighboring forests. "We wanted to look at the specific crops to identify those crops that pose the most threat in which regions," says conservation economist Roman Carrasco, of the National University of Singapore.

Carrasco and colleagues developed a model based on the von Thünen model, which predicts that land will be allocated to whatever use generates the highest net revenue. The team compiled published data related to potential earnings across the globe for 17 important crops, including wheat, soybean, and coffee. They entered that data into the model to predict which crops were likely to spread where by 2050. "We divide the world into cells," explains Carrasco. "And then we say, in this cell, what is the potential for production for each crop? What are the [crop] prices? How far away from the cities [is the cell], and how much would it cost to bring [the harvest] to the city?"

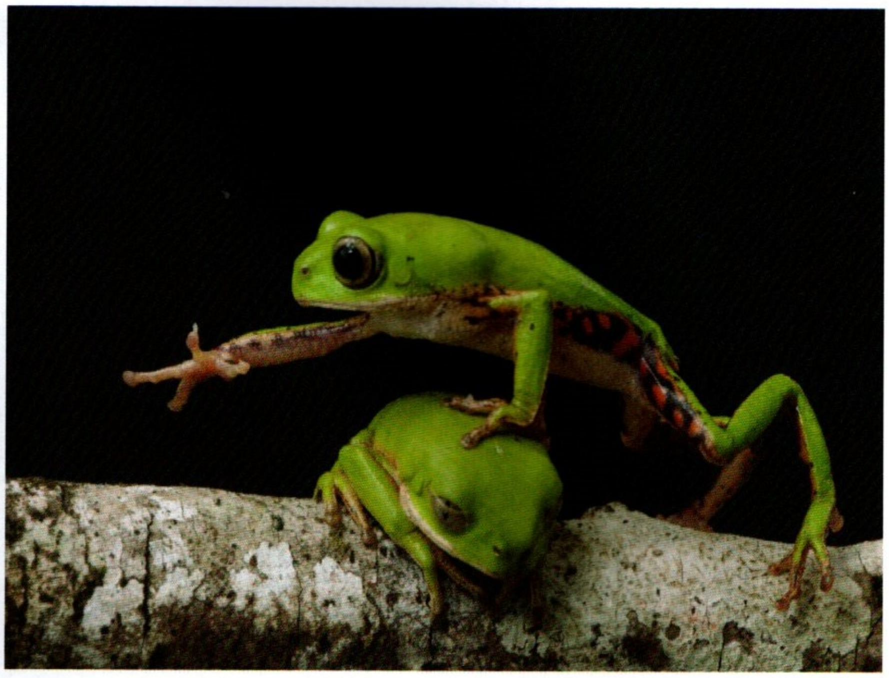
The team also included data on the distance to the nearest farm growing the same crop. "It's hard to have a completely new crop in a new place," explains Carrasco, because there is not the know-how for growing it.

The model predicted that 260 million hectares of land has high potential to be converted into cropland by 2050. Roughly 80% of this land is forested.

Some growers in Andhra Pradesh, India, use conventional farming techniques to raise maize but with patches of natural habitat throughout. Photograph: Iris Berger/University of Cambridge.

By incorporating political stability and governing style into the model, the team also learned that conflict within countries appears to be a major factor limiting agriculture's advance into some of the planet's most biodiverse habitats. Coconut, for example, is poised to expand in the Democratic Republic of the Congo. Carrasco and colleagues posit that the main factor holding this and other crops back there is political conflict, which discourages foreign investment. The same is true for other countries facing political instability, such as Venezuela and Angola.

"What we think is that, when that political instability is resolved, these areas will be under big threat of conversion from crops," says Carrasco. He

Lilac-breasted roller** (Coracias caudatus) **at South Luangwa National Park, Zambia (l). Researchers are using models to determine where in Zambia the land could be farmed with minimal biodiversity loss. Photograph: Hans Hillewaert, CC BY-SA 4.0.

Two male** Phyllomedusa rohdei **frogs in the Atlantic Forest in Bahia, Brazil. Some 85% of this forest has been cleared for agriculture, pasture, timber plantations, and cities. It remains home to 2200 species of fauna and 20,000 species of plants. Photograph: Renato Augusto Martins, CC BY-SA 4.0.

hopes that, by identifying this risk now, conservation organizations can engage with governments in these regions to develop careful plans for where to expand agriculture and where to protect wildlife.

The study also showed that, if growers could reach the greatest possible yields for their regions, the need for additional farmland by 2050 would drop by 27%. Closing this yield gap, Carrasco estimates, would prevent 20% of species extinctions for birds and 6% for mammals. Encouraging farming practices that raise the productivity of three crops in particular—rice, soybean, and wheat—would be especially impactful, says Carrasco. "The demand is massive for those three, and they are in areas that have a lot of biodiversity."

Expand versus intensify

This potential to save natural landscapes by increasing production on existing farmland is at the heart of many debates about reconciling food demand and biodiversity. Since the early 2000s, conservation scientist Andrew Balmford, of the University of Cambridge, in the United Kingdom, has explored the effects of what he calls *land sharing* versus *land sparing*.

Land sharing makes agricultural land more hospitable to wildlife through practices such as incorporating hedgerows and ponds and limiting the use of chemicals. But land sharing can produce lower yields, requiring more farmland, explains Balmford. "You make the farm friendlier for wildlife; that's great. But you're reducing your production, and that simply means the problem is going to leak somewhere else."

Alternatively, land sparing aims to increase yield even at a cost to biodiversity within agricultural areas, which can free up space for natural habitats elsewhere.

Balmford's team first explored the impact of these two approaches using data on the population densities of bird and tree species sampled across Ghana and India. The sampling sites spanned high-producing monoculture to more low-yielding fields of diverse crops interspersed with forest. For each species in each country, the researchers studied the relationship between the abundance of individual species and crop yield. They then used those relationships to project whether each species would be better off if food demands were met through land sparing, land sharing, or some intermediate.

The research, reported in *Science* in 2011, suggests that most bird and tree species are negatively affected by agriculture, and the majority of these species are sensitive to even low-yield farming. Land sparing, then, would allow for greater population sizes for most bird and tree species across the landscape as a whole.

Balmford and colleagues continued this research in other regions with additional species, looking to see if the findings held. "We had people looking at grasses and sedges and daisies and dung beetles, and we were still getting the same broad pattern," says Balmford, noting that the pattern held for the majority of species in each taxon and in every location.

Monocultures, such as this wheat field in Ohio (l) reduce biodiversity, including the biodiversity of insect species beneficial to farming. Photograph: Nyttend.

Some growers use wildflower strips, such as this one on a Montana farm, to lure beneficial insects and increase biodiversity. Photograph: US Department of Agriculture Natural Resources Conservation Service.

In a 2021 review in the *Journal of Zoology*, which includes work from his own group and others, Balmford reports that, of over 2500 species studied, over three-quarters survive better without agriculture, and of those, the large majority maintain greater population sizes under land sparing.

Balmford says that his findings have been criticized by those who equate higher yields under land sparing with unsustainable farming inputs, including chemical fertilizers and pesticides. "We don't think it needs to be that at all," says Balmford, noting that the yield could also increase through additional labor or farming knowledge and under certain traditional farming practices.

Berger was struck by Balmford's findings and wondered whether—if land sparing really is better for biodiversity—there could be ways to ramp up the yield sustainably. "There's no use in increasing the yield, and then, in 10 years' time, the soil is degraded," says Berger. She wondered whether the ZBNF movement gaining momentum in Andhra Pradesh could be part of the answer.

ZBNF began taking hold in Andhra Pradesh as early as 2016, says agricultural scientist Zakir Hussain, who leads science and research for the Farmer Empowerment Organisation (RySS), the government-supported nonprofit responsible for helping farmers in Andhra Pradesh transition to ZBNF.

In 2018, the government of Andhra Pradesh announced a push to transition all of the state's farms to ZBNF in a bid to improve the livelihoods of smallholder farmers and to restore the region's biodiversity and ecosystem services. Growers began eschewing synthetic pesticides and fertilizers in favor of more cost-effective and sustainable options, such as managing pests with botanical extracts or creating perches for insect-eating birds.

Today, Hussain says that about 800,000 farmers in Andhra Pradesh practice ZBNF, which the government now refers to as *community managed natural farming*. Anecdotal evidence that ZBNF can match or even surpass conventional farm yields is mounting, and the practice is spreading quickly. ZBNF farmers become "ambassadors," says Hussain. "They spread natural farming practices to other farmers."

Scientific research exploring ZBNF practices is just beginning to emerge. In a February 2022 issue of the journal *Sustainability*, Hussain and colleagues described a field experiment at study sites across Andhra Pradesh in which they found no difference in yield between plots managed with conventional and those managed with ZBNF practices for a variety of crops.

Berger wants to know how ZBNF affects birds. She wonders whether the practice may make farms more habitable for birds while also increasing yields so that more wild habitats can be spared. She surveys the density and diversity of avian species on ZBNF and conventional farms, as well as in forests untouched by agriculture. She also records the proportions of natural habitat nested within the farmland.

Ultimately, Berger, who counts Balmford as one of her dissertation advisors, will enter this data into a mathematical model that will optimize the agricultural landscape to meet food production goals while maximizing the density for each bird species. She will learn the ideal amount of spared habitat versus farmed land, the optimum proportion of ZBNF versus conventional farms, and the most effective proportion of natural habitat patches within farmland.

The results, she says, could suggest a combination of different approaches in different areas. Maybe in some places, for example, ZBNF produces lower yields, so some proportion of conventional farms are required to spare the natural habitat that specific bird species require. But perhaps these conventional farms need to include some optimum number of habitat patches to maintain pollinators and other ecosystem services critical for their yield. "It's very complex and probably very case specific," says Berger.

How to measure biodiversity?

Researchers are also using models to pinpoint where, in an ideal world, farming could expand at the least cost to biodiversity. But the work hinges on estimating one variable that is especially difficult to pin down: biodiversity itself.

Biodiversity is the variety of life on Earth. This variety exists at different scales, such as whole ecosystems, species, or genes within species. Researchers recording biodiversity simply cannot count everything. So they make choices. Some may tally all vertebrate or plant species or give higher weight to endangered species or use only birds or another representative group. Many combine several of these measures into a single biodiversity index.

When Crawford began reading land prioritization studies, he recognized that researchers often measure biodiversity in different ways. "All valid and defensible methods," he says. But he wanted to understand how seemingly small differences between methods ultimately influence land-planning recommendations.

Crawford began with a land-use model called *agroEcoTradeoff*, previously developed by colleagues at Princeton and elsewhere. He used this model to project where to convert land to farmland in Zambia to minimize biodiversity loss while meeting crop production needs in this country with a rapidly growing population and economy.

Crawford ran the model with four previously published biodiversity indices and, each time, received different recommendations for where to expand agriculture. An index focused on vertebrate species richness with additional consideration given to species' range sizes, for example, suggested that agricultural expansion would be best placed in the southwestern portion of the country. Meanwhile, an index focused on how rare, intact, and well-protected different vegetation types are instead suggested that farmland should expand along the eastern portion of the country. Indeed, when comparing recommendations for where to expand agriculture between pairs of indices, the average overlap was only around 2%.

The team then developed a series of their own indices so that they could systematically vary different components to understand what exactly causes biodiversity indices to return such divergent recommendations. They found that focusing on different groups of animals could change the recommendations dramatically. Bird diversity in Zambia, for example, was least harmed by agriculture expanding primarily in the southwest, whereas amphibians would be better off if agriculture moved into the southern and northern tips. Other decisions affected the recommendations too, such as the spatial scale of the data included and how much weight was given to range size when calculating species richness. Even the simple choice of whether to combine different biodiversity measures by taking the arithmetic mean versus the geometric mean could sway the recommendations in meaningful ways.

"In order for these sorts of prioritization analyses to be taken seriously in conversations about land-use priorities and future land-use development, researchers need to be very careful and thoughtful about how they are quantifying biodiversity and transparent about the decisions that they are making," says Crawford.

From research to practice

As researchers search for the best possible balance between farmland and biodiversity protection, they also face the difficulty of translating this ideal landscape into reality. "Simply doubling yields doesn't halve the space that farmland takes up," says Balmford. "It will tend to shrink it, if you look at global averages over time for most commodities in most places. But it doesn't halve it." The trouble, as Balmford explains in his 2021 *Journal of Zoology* review, is that a rise in yield could lower prices and so stimulate consumption, thereby requiring more land. Higher yields could also increase growers' incomes, which might incentivize putting that money into more land clearing. Land sparing, then, works best when increased yields are accompanied by policy measures aimed at protecting biodiversity, such as land-use zoning and economic incentives to restrict the area covered by agriculture.

But these policy changes require decision-makers to recognize the importance of biodiversity protection and the value of academic findings. One potential issue is that the academic research in this field is focused on protecting biodiversity across the globe, but the researchers are often based in North America and Europe. "There are ethical arguments for research to be done by people who represent the

Further reading.

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places making these decisions," says Crawford.

"For this research to have an impact," says Carrasco, "it should be coproduced from the earliest stage. So when you are designing your research, you should [work] together with the decision-makers of the country and try to understand the questions they want to answer."

Policymakers also need clear measures of biodiversity and direct links between biodiversity and human benefit. Carolina Soto-Navarro, of the UN Environment Programme World Conservation Monitoring Centre in Cambridge, in the United Kingdom, and colleagues argued in a 2021 perspective in *Nature Sustainability* that countries need a multidimensional biodiversity index (MBI). Much like the GDP is a measure of economic health, Soto-Navarro and colleagues say, the MBI would be a measure of a nation's biodiversity health.

The MBI would be calculated using a score card that tallies metrics of biodiversity, as well as key benefits that biodiversity offers to people—from aesthetic pleasure to the regulation of environmental processes, including carbon cycling and air quality. The MBI is still in a proof-of-concept phase, says geographic information scientist and landscape ecologist Franz Mora, of the National Commission for Knowledge and Use of Biodiversity (CONABIO), in Mexico City, Mexico. Mora, a coauthor on the perspective piece, is developing an MBI for Mexico while researchers in Vietnam, South Africa, and Switzerland develop their own.

CONABIO has been offering biodiversity data to government agencies and nongovernmental organizations for over two decades now, says Mora. But never as a single measure. "When everybody asks [about] the condition of biodiversity in the country, it is really difficult to explain, because you have to use all of these sources of information," says Mora. The hope is that an MBI will offer a clear benchmark for tracking biodiversity health over time.

Proof that a policy change will work also helps. "We need hard-core evidence for the governments to convince them and bring policy interventions," says Hussain. And the same goes for growers, whose livelihoods depend on these decisions. Initially, RySS had difficulty convincing farmers that growing crops 365 days out of the year could increase production and also protect the soil. So RySS led demonstrations throughout the state. Now, says Hussain, "the farmers are seeing the results."

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