Foodscapes

Toward Food System Transition

The Nature Conservancy

International Institute for Applied Systems Analysis
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CONTENTS

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Diverse agricultural landscape in Myanmar.

Executive Summary

Foodscapes: Toward Food System Transition

EXECUTIVE SUMMARY

This report introduces *foodscapes*. Foodscapes are the geographical components of the global food system, a combination of production system and place that represents the world food system spatially. Mapping and analyzing foodscapes reveal the transitions needed on the ground to meet this century's most pressing challenge: the threats posed by climate change, biodiversity loss, and increased demand on the integrity of the global food system.

Foodscapes help all those involved in organizing and reforming the world food system — policymakers, producers, community leaders, researchers, journalists, decision makers in the private and public sectors in general — to take the vital first step of moving from a global analysis to what needs to happen where and how it might come about. That first step revolves around nature-based solutions: ways of managing food production systems that restore and rebuild natural systems, rather than exhaust them.

The report maps the world's foodscapes and assesses their current condition. It looks at the threats they face, and the opportunities that exist through nature-based solutions to transition to a food system able to meet demand while conserving biodiversity, rebuilding ecosystem services, mitigating climate change and increasing the resilience necessary to weather climate change impacts. The report includes examination of what the transition could look like in 10 specific foodscapes (see Foodscapes in Focus).

It also locates and quantifies the global benefits, especially climate change mitigation, associated with a food system transition to nature-based solutions.
Key findings:

- Global carbon benefit on croplands and grazing lands ranging from 2.2 up to 3.3 $GtCO_2\ y^{-1}$ through restoration; 4.4 up to 14.6 $GtCO_2\ y^{-1}$ through agroforestry; and 2.2 up to 5.0 $GtCO_2\ y^{-1}$ through improved soil health practices;
- Global habitat restored on up to 428 million hectares of crop and grazing lands and up to 1267 million hectares of habitat-friendly farming;
- Increase of edible food from sea of between 36-74% by 2050 through improved management of wild fisheries and restorative aquaculture;
- Reduction of 15% in water removals for agriculture; and
- Reduction of almost 50% in synthetic nitrogen fertilizer use, through nutrient management and substitution with organic sources

This is not a utopian manifesto. The analysis in this report takes the world as it is as a starting point. The full transformation of the global food system will involve an array of other strategies, around diets and nutrition, reducing food waste and eliminating deforestation and land conversion, which are not dealt with in this report. The analysis focuses on the value of specific transitions to the ultimate achievement of full food system transformation. The results of such transitions, as this report shows, are not modest, and achieving them will not be straightforward. This report helps us to chart a way forward.

A NECESSARY TRANSITION

The world food system employs 1 billion people and accounts for about 10% of global GDP. It also accounts for up to 35% of global emissions and is the biggest single driver of biodiversity and habitat loss. The global food system has in some ways been extraordinarily successful. The global predictions of food shortages that were common a generation ago never came to pass, although local crises of famine and food insecurity persist. Malnutrition takes new forms, with incidences of obesity and other dietary illnesses exceeding those of undernutrition.

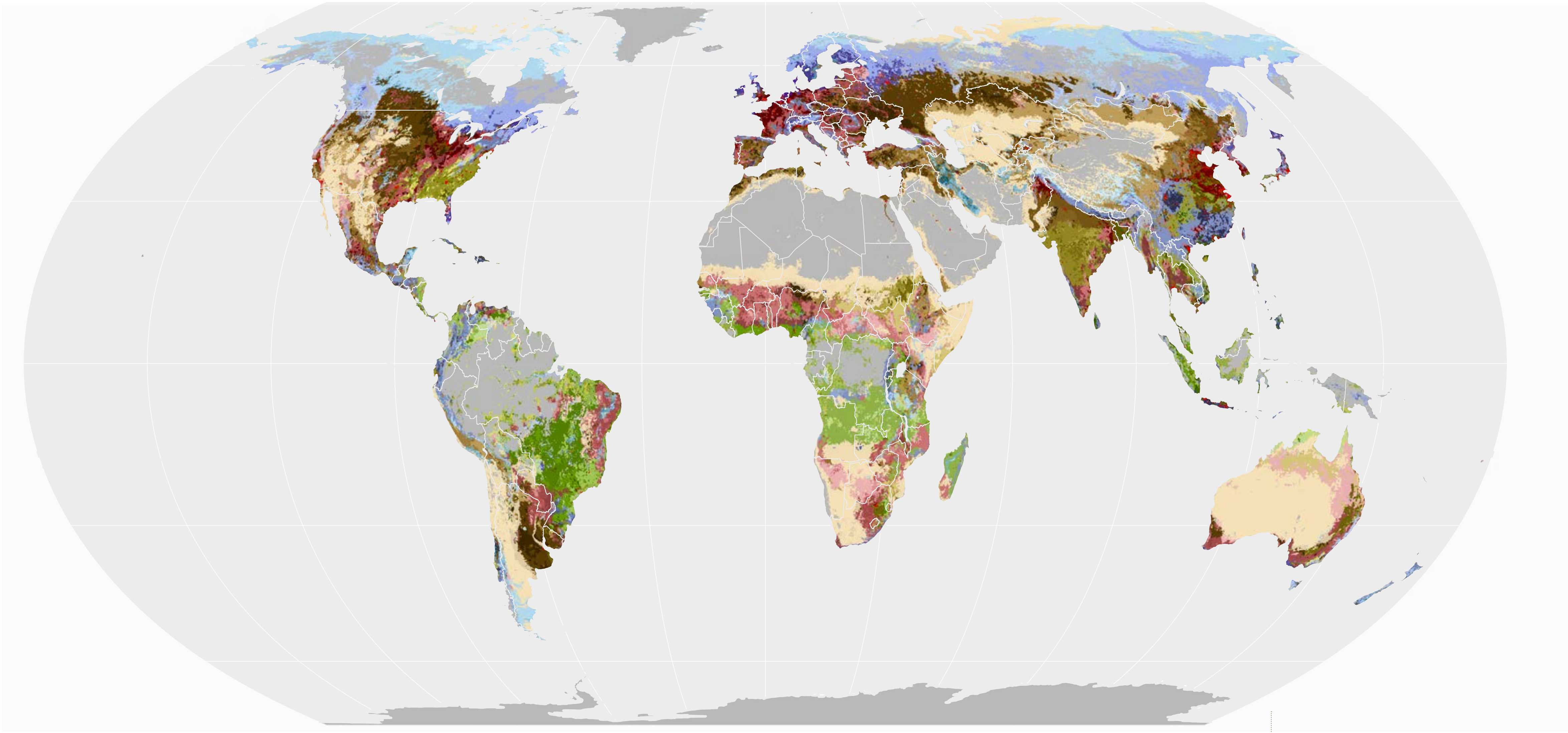
We now face a different type of threat. The climate crisis has made clear that the success of food systems in meeting this demand in the past has, ironically, created a critical new challenge for the future. Food production systems have intensified, but sustainable intensification has been the exception, not the rule. Intensification has meant greater pressure on soils, more biodiversity loss, increased agrochemical and fertilizer use and higher emissions. Climate change can lead to lower yields and threatens to destabilize production systems at exactly the moment when rapidly rising demand puts more stress on those systems.

Change is coming. It will either come as economic and social disruption, or as part of a managed transformation. At the heart of the transformation should be a focus on rethinking and regenerating the individual foodscapes that underpin the global food system.

A growing body of science, synthesized in the recent "Growing Better" report from the Food and Land Use Coalition, has laid out the necessary transitions at a global level. Research is also clear on the urgency of the food system challenge and the limited time remaining to address it. The next decade is crucial if we hope to keep Paris Agreement targets and biodiversity thresholds within reach. Many critical food production systems around the world are already facing multiple pressures; their productivity and output is eroding, through over-exploitation of the ecosystem services like water, soil organic matter and agro-biodiversity that farmers, fishers and grazers depend upon.

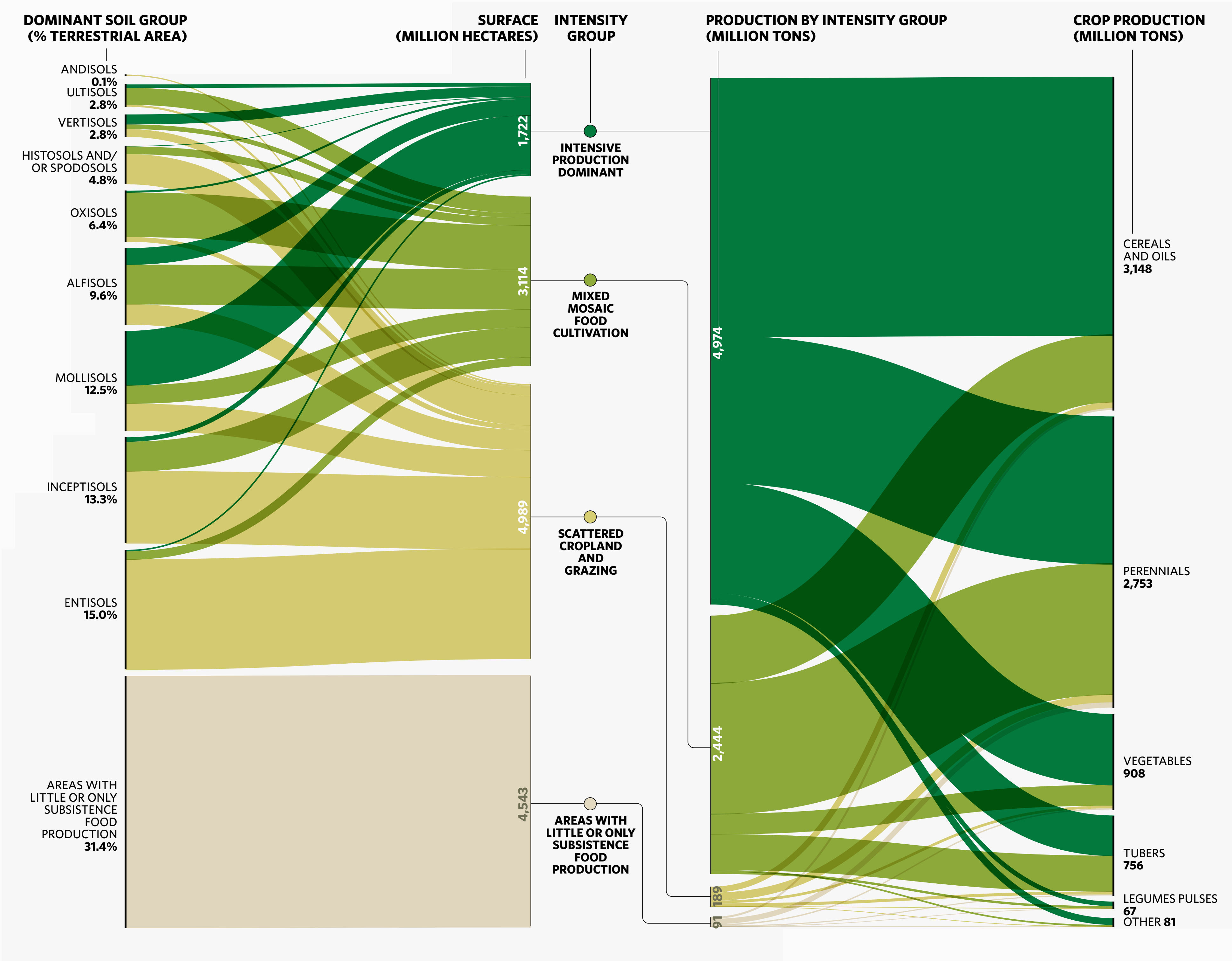
Making a food system transition work is the most urgent challenge the world faces. Done right, the transition makes economic as well as environmental sense: the hidden costs of the current world food system are estimated at $12 trillion, $2 trillion more than the system generates (FOLU, 2019). Central to that necessary transition are "Nature-Based Solutions" that have the potential to transform the world's foodscapes, helping restore ecological function and the resilience on land and at sea.

FIGURE 1. GLOBAL FOODSCAPE MAP



GLOBAL FOODSCAPE MAP visualizing 86 terrestrial foodscape classes at 5 km by 5 km resolution. Owing to the large number of classes, a legend is not shown. Map key with complete list of foodscape classes can be found in Annex 1

FIGURE 2. GLOBAL FOODSCAPE INTENSITY GROUPINGS AND CROP PRODUCTION



FOODSCAPES: A SPATIAL ANALYSIS

A foodscape is a terrestrial or aquatic food production area defined by a series of distinct biophysical attributes and management patterns, which can be mapped. They cover all parts of the globe where food is produced. When mapped, they form a mosaic at the subnational level around the world. Due to their unique combination of biophysical and management attributes, they can be considered as functional planning units to complement jurisdictional-based approaches.

This report presents the results of the first global analysis and mapping of foodscapes. Some foodscapes occur in relatively small, confined areas while others are widespread and occur on multiple continents. Examples of the latter include semi-arid grazing systems that are widespread on all continents, and "breadbasket" foodscapes with intensive grain and oil crop production in temperate plains with good soils. As is to be expected, foodscapes are very diverse, and the global mapping resulted in more than 80 foodscape classes. Defining and mapping foodscapes

FIGURE 2. Global Foodscape intensity groupings and crop production
For the purposes of this figure, the Global Foodscape classes have been consolidated into groupings of similar biophysical attributes on the left side (Dominant Soil Group), and similar management attributes in the middle of the figure (Intensity Group). The biophysical groupings are identified by the dominant soil type found in the foodscape classes. Soil type is determined by the complex interaction of parent material, climate, vegetation, terrain, time, and human activity. Foodscapes will thus contain a variety of soil types in complex associations. The management groupings are defined based on the areal extent of croplands in the foodscape overall, and the intensity of the management systems within each grouping. Areas with little or only subsistence food production may have some low intensity cropping and grazing which can be important for local communities. The crop output in fresh weight of major crop groupings from each foodscape is represented on the right.

makes it easier to envision which nature-based solutions are most relevant to the transition the foodscape will need to make to accommodate demand, conserve ecosystems and the services they provide, and mitigate greenhouse gas emissions.

Global level transitions are often hard to translate into local context: the solutions are too abstract, too removed from economic and political realities. The foodscapes concept is intended to help bridge that gap, providing a sense of the opportunity for nature-based solutions to deliver benefits globally as well as foodscape-specific understanding of potential interventions and their impact. While caution should be taken when using a global-level product such as the foodscapes analysis, it can provide useful insight that can be further developed, adapted and applied using local, place-based knowledge.

Any analysis of this type faces challenges. Marine data is not as comprehensive as terrestrial data and lacks attributes enabling detailed mapping at a sub-national or sub-regional level. The marine realm needs more work and attention from policymakers, economists and scientists to build a transition framework for marine foodscapes equivalent to the one this report presents for terrestrial foodscapes. Given the important role fish and seafood could have in supporting the transitions needed, such work should be a priority for policymakers and the research community moving forward.

A CALL TO ACTION

This report can be used as a starting point for planning transitions in global food systems. It suffers from the gaps and omissions inevitable in any effort to conduct a global-level spatial analysis. These omissions — the missing datasets, the unaddressed socioeconomic variables, the lack of comparable analysis of the marine as opposed to the terrestrial realm — show how much work still needs to be done to provide policymakers, community leaders, and market actors with the information and evidence needed to inform their decision-making. This report is also a call to action to the research community, civil society and policymakers to move further and faster on addressing these omissions.

It is also a call for a policy response proportionate to the challenge. There is growing consensus on the high-level changes necessary in the global food system. Now it is urgent that we proceed to the next step: detailed planning and implementing of food system transition at national and subnational scales. We need policy frameworks and market incentives to get behind that transition, moving beyond the inertia of business as usual and vested interests.

FOODSCAPES IN FOCUS BRIEFS

In order to show policymakers, community leaders and decision-makers how nature-based solutions can support food production in specific foodscapes, we have taken an in-depth look at specific subnational foodscapes. The case studies presented are:

Argentina Gran Chaco Foodscape
Halt biodiversity loss through mixed land use

Arkhangai Foodscape
Community-based conservation to promote rangeland health through land rights

Central New Zealand Aquaculture Foodscape
Aquaculture diversification for resilience

Chesapeake Bay Watershed Foodscape
Restore natural habitat to enhance success of nutrient reductions

East Kalimantan Foodscape
Protect and enhance habitat through adaptive land use

Granada Foodscape
Ensure climate resilience by promoting a return to traditional practices

Mopti Foodscape
Governance systems to manage land use conflicts

Punjab-Haryana Foodscape
Policy and incentives to improve crop production, water security, and human health

San Joaquin Valley Foodscape
Balancing food production and biodiversity under water scarcity

Upper Tana River Basin Foodscape
Innovate technical solutions for market-oriented smallholders

FOODSCAPES - TOWARD FOOD SYSTEM TRANSITION

Introduction

INTRODUCTION

The health of the planet and all its inhabitants is profoundly linked to the many different ways we feed ourselves. Despite relative success in supplying the current population of more than 7.5 billion, our food system is failing in important ways. The hidden costs of our global food system, in terms of malnutrition and environmental damage, include approximately 11 million excess deaths annually,[1] greenhouse gas emissions accounting for 35% of humanity's contribution to climate change, and extensive loss of habitat and biodiversity due to land conversion, pollution, and other factors. The economic costs of these impacts are credibly estimated to be higher than the entire market value of the global food system.[2]

The world is at an inflection point. Planetary boundaries that seemed abstract and distant even a decade ago are much less so today. Absent revolutionary change, we know the future: pressure on the global food system will continue to grow. Demand for more and different types of food will increase as income increases and diets change. This demand shift is expected to peak over the next generation — exactly when climate change will impact the world at a higher level.

We are already seeing these impacts playing out in real time and it is likely that we're only at the beginning of learning to manage, mitigate and adapt to the increasingly extreme conditions climate change is expected to create.

There is clear scientific evidence that business as usual in the global food system will undercut efforts to tackle today's health, climate and biodiversity challenges.[1-3] Attempting to continue to feed a growing population in the same ways we always have will result in failure of the systems that support life, livelihoods, and human well-being.

Recent work from multiple credible groups has examined the global food system comprehensively. Their findings frame hopeful future scenarios as a compelling call for action, and provide recommendations and guidance that encompass multiple food system elements including production, consumption, nutrition, governance and equity (see BOX 6, p.82). The systems perspective is especially useful because food systems are multidimensional, and it isn't always easy to see how changes in a single practice or action can cause cascading effects and unintended consequences.

Box 1 Key statistics and trends

Climate
The global food system is responsible for at least one-third of anthropogenic greenhouse gas (GHG) emissions. Approximately 20% of these emissions come from land conversion, 44% from crop production (including livestock and fish farms), with the remaining from processing and the supply chain. Agriculture can eliminate or recapture a significant amount of these emissions and thus is a necessary part of the global response to climate change.[4]

Biodiversity
Agricultural expansion continues to be the primary driver of global deforestation and biodiversity loss. Species extinction rates are accelerating and are higher than the average rate estimated over the past 10 million years,[5] with agricultural activities alone threatening 24,000 of the 28,000 (or 86%) species at risk of extinction.[6]

Hunger
A global assessment in 2020 found that between 720 and 811 million people faced hunger, or nearly one-tenth of the global population. World hunger has continued to rise driven in part by conflict disrupting food systems and economies, extreme weather events associated with climate change, and the COVID-19 pandemic. Nearly one in three people in the world (2.3 billion) did not have access to adequate food in 2020 — an increase of almost 320 million people in a single year (FAO).[7]

Nutrition and Health
Climate-related disasters, droughts and extreme weather events dramatically impact what food is available to children and families, as well as the quality and price of food. The greatest impact of malnutrition falls on children and adolescents from the poorest and most marginalized communities.

Grapes on a vine in Granada.

Loja, Granada, Spain.
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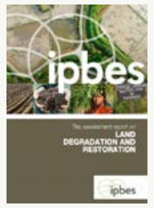
Box 2 | Recent reports and key messages

The International Panel of Experts on Sustainable Food Systems (IPES-Food) report, “From Uniformity to Diversity: A Paradigm Shift from Industrial Agriculture to Diversified Agroecological Systems” (2016) calls for the transformation of the world’s food systems.[8] The report clearly shows that such global transformation will require more than “tweaking of business-as-usual practices,” and must also include attention to poverty, access, social equity and power.



The International Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) “Assessment Report on Land Degradation and Restoration” (2018), and related paper in Nature Sustainability (2020) highlight the urgency of action and call for changes in production and consumption to stave off the worst impacts of land degradation.[9] Both publications identify agricultural expansion as the most direct driver of land degradation and suggest landscape approaches and the elimination of perverse incentives as essential features of solutions.

The EAT-Lancet Commission on Food, Planet, Health report, “Food, Planet, Health” (2019), and related paper in Nature Food (2020) identify food as the single strongest lever to optimize human health and environmental sustainability on Earth.[1] This report provides a framework for globally healthy diets with regionally adapted targets and outlines the impact of combined diet, food waste, and production system improvements on climate and land use. The report also suggests five strategies to achieve the best-case scenario, including diet change, reorienting agricultural policy toward producing healthy food, sustainable intensification, governance of land and oceans, and halving food waste.

The Food and Land Use Coalition (FOLU) report, “Growing Better: Ten Critical Transitions to Transform Food and Land Use” (2019),[2] outlines an agenda for reforming food systems that “would enable food and land use systems to provide food security and healthy diets for a global population of over 9 billion by 2050, while also tackling our core climate, biodiversity, health and poverty challenges.” Nature-based solutions comprise three of the 10 critical transitions outlined in this report.

The Paulson Institute, The Nature Conservancy, and the Cornell Atkinson Center for Sustainability report, “Financing Nature: Closing the Global Biodiversity Financing Gap” (2020), highlights the need to transform current economic models and market systems through a redirection of capital to incentivize conservation and restoration of nature.[10] The report calls for reforming harmful production subsidies, particularly in agriculture and fisheries — two of the largest drivers of global biodiversity loss — and proposes pathways for governments to reform these existing subsidies while supporting sustainable farming and fisheries practices to help deliver a net positive effect on biodiversity.

Intact forests are part of the diverse Gran Chaco foodscape in Argentina.

THE OPPORTUNITY FOR ACTION
The good news is that a growing body of evidence suggests that food system transformation can be a means to simultaneously address our climate emergency, improve food and water security, promote human health, and protect biodiversity. Estimates by the Food and Land Use Coalition (FOLU) suggest the costs for the transitions required in our food system will be substantial, between $3 and $3.5 trillion over the eight years between 2022 and 2030, and yet the return on this investment may be as high as $4.5 trillion.

This beneficial return includes revenues from new markets and products as well as savings from avoided externalities and inefficiencies. At the heart of this transformation are nature-based solutions: practices and actions that aim to regenerate the natural capital, such as water and soil, that food production relies on. When the hidden costs or externalities of business as usual are included in food production cost calculations, nature-based solutions can be among the most effective investments governments can make to support their people now and into the future.

Done right, nature-based solutions can deliver significant environmental benefits while also contributing to inclusive development and improved nutrition and diets. What remains less clear are the specifics: what to do, where and when, and how to enable durable transformation on the ground. This report is intended to help answer those questions by estimating — in a spatially explicit and global manner — the opportunity for nature-based solutions to support restoration and regeneration in food production on land and sea using a new unit of planning and analysis: foodscapes.

TOWARD TRANSITION
In the context of this report, foodscapes are defined as distinct geographic units that encompass both biophysical characteristics and food production management attributes. Individual foodscapes are place-based and the concept builds on landscape and territorial approaches that have advanced ideas around management of agriculture within a larger systems context.

The report is presented in five parts.

Section 1

Global Foodscapes presents the first global terrestrial foodscape map, based on a spatial analysis that classifies terrestrial food production globally into discrete foodscape classes representing the biophysical attributes and the management systems present in that place. This foodscape map paints a rich, spatially explicit picture of the diversity of our terrestrial food production systems and becomes the basis of subsequent analysis detailed in this report. In addition, the report draws on earlier work to present existing conditions and the potential of coastal seafood and mariculture.

Section 2

The State of Our Foodscapes is an analysis of the major ecological pressures on foodscapes, both terrestrial and near-shore marine, including the ways land, water and/or sea uses may be changing, effects of resource exploitation and climate change, as well as pollution. The results illustrate both vulnerabilities and priorities, the starting point for building a template for managed, lasting change.

Section 3

Foodscape Opportunities examines the potential of a set of nature-based solutions that could help solve the interrelated challenges of food production, climate change, water security, habitat loss, and degradation of natural resources. This section includes scenarios for nature-based solutions in foodscapes (see BOX 4, p.23).

Conclusions

Toward a Nature-Based Transition builds on the overall findings of the global analysis by interpreting the implications for achieving a nature-based transition in food systems. The section calls for action from the public sector, the private sector, and civil society in support of food producers. It acknowledges that global spatial analyses cannot capture all the attributes of foodscapes that are important for food system transition (see: A Note on the Limitations of Global Spatial Analyses, p.15).

Foodscapes in Focus

A series of 10 brief real-world, place-based examples that explore the types of interventions suitable to important global foodscape classes. Each foodscape brief captures the sociocultural particularities of each place that are fundamental to understanding adoption of all potential interventions including nature-based solutions.

Box 3 | Foodscapes for planning and analysis

Foodscapes as frames for planning and analysis are valuable in three primary ways.

- First, each individual foodscape provides a basic unit upon which multi-dimensional analyses can be built. Because each class of foodscape represents a cluster that is a combination of biophysical and management variables, it enables grouping of like with like and captures differences that influence the potential of different interventions. Thus, specific practices identified as suitable in a particular place within a foodscape class can be expected to be widely applicable within the foodscape class, although the social-political and cultural context may make adoption more or less likely.

- Second, foodscapes enable the flexible definition of distinct units of analysis and management for research and action. Foodscapes overlap with distinct supply chains, form a mosaic within political units and jurisdictions, and overlay agroecological zones and biomes. That means that for anyone, policymaker or economist, analyst or community leader, foodscapes can provide a spatial unit for mapping a path to transformation.

- Finally, because individual foodscapes overlap but remain complementary to local jurisdictions and supply chains, it helps those engaged in initiatives involving both or either to develop scaling strategies more easily.

TOWARD FOOD SYSTEM TRANSITION

This analysis takes the world as it is as a starting point. It provides a frame for understanding the distribution of current threats, and how far the world can move toward achieving goals for climate, water, biodiversity and food production via nature-based solutions implemented in foodscapes as they exist today. Unlike some global scenarios, this analysis does not attempt to restructure the world's food systems via interventions that affect trade, or require major land-use changes, or significant shifts in cropping patterns. In this way, the emphasis of this analysis is on short-term potential, working within the existing structures of food production worldwide.

This work recognizes — and demonstrates — that nature-based solutions alone will be insufficient for achieving our collective goals. Food systems (see BOX 4, p.23) are complex. Further interventions to support transitions in policy, diets, land use, economic development and supply chains will be needed to transform fundamental drivers of the food system.

At the same time, this analysis suggests there is enormous potential for nature-based solutions to help support the transitions necessary for lasting transformation in the global food system. Nature-based solutions cannot only improve livelihoods and public health, but also regenerate rather than deplete resources, mitigate rather than exacerbate climate change, and restore and protect rather than accelerate the destruction of biodiversity and habitat.

This is not a modest agenda for reform: achieving nature-based solutions at the scale this report suggests is needed would ultimately result in a major transformation in the way land and water resources are managed today, and set the world on a new path for the future.

Cattle grazing on pasture land in Argentina's Gran Chaco foodscape.
© Karina Diarte

Box 4 | Definitions

Food System
The food system is the complex web of activities — and the beliefs and values that shape these activities — associated with producing and consuming food. This includes the production, processing, transport, preparation, consumption, and disposal of food (including food by-products and waste).

Foodscape
A foodscape is a geographic location characterized by a distinct combination of food production management characteristics, and the biophysical attributes of the wider land- and seascapes within which it is embedded. The foodscape, as a unit, encourages an integrated perspective, and mapping foodscapes based on globally available data sets provides a spatially explicit platform for interventions. Additional detail on the methodology and data used to define the foodscape classes in this report can be found in the supplemental material.[11]

Nature-Based Solutions
Nature-based solutions include regenerative and restorative methods of food production, agriculture, aquaculture, mariculture, and fisheries — along with land management, including protection and restoration of habitat — that support climate stabilization, resilience, biodiversity, food production, and livelihoods. In all cases, nature-based solutions are designed to support principles of fairness, equity and participation. The following elements comprise the definition of nature-based solutions within the context of this report:

- Agroecology and regenerative agriculture practices are those ecologically sound methods that build (restore) natural capital while providing healthy food and secure livelihoods. The many relevant practices here apply to both cropping and grazing systems. Practices include agroforestry, nutrient management, irrigation management, and soil health management practices.
- Restorative aquaculture and fisheries, mariculture production, and fisheries methods that restore ecological function and rebuild natural capital that has been degraded due to historic production practices, pollution, and exploitation of fisheries.
- Protection and restoration of natural ecosystems, including halting conversion of forest and grasslands for agriculture, and restoration of degraded forests and grasslands. It incorporates edge-of-field and riparian habitat restoration that increase agrobiodiversity in agricultural landscapes.

A NOTE ON THE LIMITATIONS OF GLOBAL SPATIAL ANALYSES
Global analyses by definition oversimplify the world, both in the systems they try to describe and their inability to address social equity, poverty, livelihoods and community-level analysis. These limitations are exacerbated in a global spatial analysis due to the limited availability of spatially explicit datasets addressing critical sociocultural, economic, and demographic variables. For those variables that are mapped globally, the spatial resolution, temporal duration, and thematic coverage can also present constraints. This report therefore analyzes the technical potential of nature-based solutions in foodscapes, rather than attempting to model dynamic socioeconomic phenomena such as adoption patterns and pathways.

Another major shortcoming of the global spatial foodscapes analysis is inadequacy in the currently available data to understand marine and freshwater (wild caught and aquaculture) systems. Data inadequacy exists for terrestrial systems also, especially for animal agriculture — but the challenge is greater in aquatic and marine systems where satellite information is less resolved, and fish populations can range widely across habitats during their life cycles.

The lack of spatially explicit aquaculture production data limits the capacity to view production from aquatic environments at scales that reach beyond, or work across, national boundaries, because the ability to map foodscapes in marine environments is currently tied to national boundaries and statistics. This limitation also affects the way in which the biophysical factors influencing aquaculture production can be linked to production factors: the species grown, systems used and the production output achievable. Due to these limitations, this report focuses primarily on terrestrial foodscapes, and includes attention to mariculture systems for which analysis exists.

SECTION 1

Global Foodscapes

The world's foodscapes are diverse, shaped by their biogeographic and sociocultural contexts. While many parts of the world may grow a particular crop or system of crops, or cultivate and harvest various marine species, different cultural practices and geographic and economic contexts result in outcomes that vary from foodscape to foodscape.

Targeting interventions and understanding the potential for nature-based solutions in food systems requires an analysis sensitive to the distribution of both biogeographic conditions and current use and management. For this reason, the analysis in this report began with an attempt to map and classify the world's foodscapes. Numerous limitations exist in the ability to represent some important production systems in this type of global analysis. These include freshwater fisheries and inland aquaculture, marine fisheries, urban agriculture and forest products. These important systems, while not included in the mapping, are highlighted in the final portion of this section.

TERRESTRIAL FOODSCAPES

The report identifies terrestrial foodscapes (FIGURE 1) that are distinct based on their particular combination of biophysical and management-related variables. To make the identifications, researchers collated and harmonized the best global spatial datasets available (at a 5 km by 5 km resolution) on biophysical and management properties of terrestrial food production systems as they exist today.

CLASSIFICATION

Using a two-tier unsupervised classification of these datasets, Researchers identified distinct clusters of variables that define unique foodscape classes.[1]

It is important to note that this form of variable-based clustering is predominantly data-driven, highlighting regions of highly similar distinctive characteristics, rather than areas described based on an a priori defined classification system. These clustering efforts focus attention on specific management variables that enable rough separations of foodscapes based on crop and animal production intensity. The resulting clusters range from low-intensity to high-intensity foodscapes across a range of biophysical environments.

Overall, the foodscape classification showcases the diversity of production systems around the world. Despite the relatively coarse resolution, which necessarily simplified the tremendous diversity found in the world's food production areas, more than 80 distinct foodscape classes emerged from the analysis. Some of these classes occur in quite small geographic areas, whereas others are widespread over large tracts of multiple continents, highlighting the need for diverse approaches to scaling interventions, including nature-based solutions.

The analysis shows that two-thirds of global terrestrial area contains food production areas within the wider landscape. This does not mean that 66% of Earth's terrestrial area is being cropped and/or grazed. Rather, the foodscape analysis reveals how food production does not exist in isolation from its surrounding areas. Food production is one aspect of the foodscape, but there are other aspects and uses, including natural and urban areas to be considered.

The additional 30% of terrestrial area is classified as having little or no food production. These areas range from forested landscapes to deserts and arctic tundra, and also include some of the world's densest urbanized lands. While they are classified as "non-food producing" in this global analysis, they do include some forms of production, for example, hunting, gathering, and low-intensity agriculture, often by Indigenous peoples, as well as urban agriculture. These areas can be important for food security and diet diversity for local communities.

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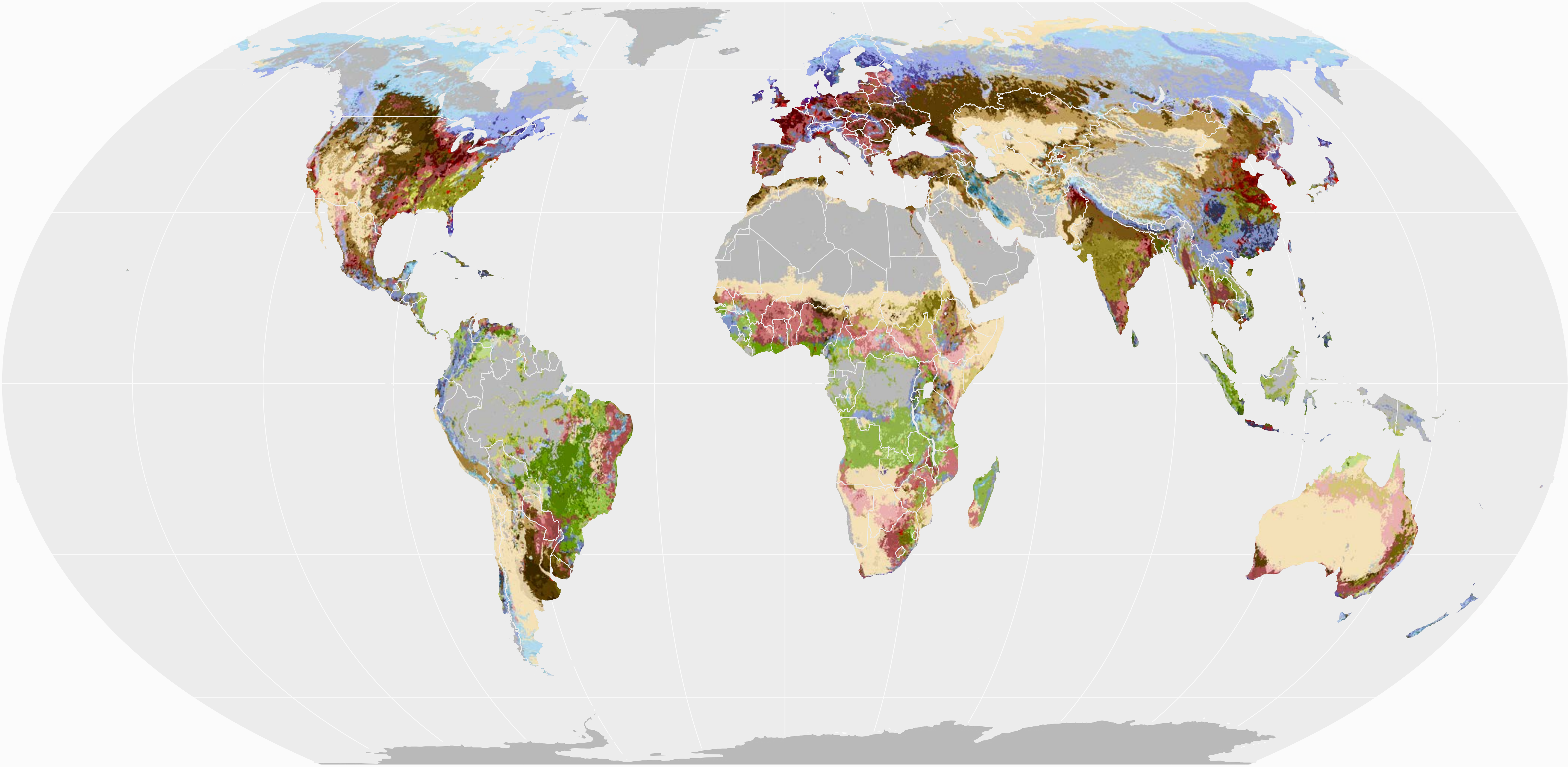
Agricultural lands and intact forests near the Hunhe River, China. © Liu Yuesheng

FIGURE 1. GLOBAL FOODSCAPE MAP



Global Foodscape Map visualizing 86 terrestrial foodscape classes at 5 km by 5 km resolution. Owing to the large number of classes, a legend is not shown. Map key with complete list of foodscape classes can be found in Annex 1.

GROUPING

Following the unsupervised classification, expert examination of foodscape class data and maps was used to assign terrestrial foodscape classes to groups representing broad intensity categories (FIGURE 2 AND FIGURE 3).

An important feature of the foodscape concept, as noted in the discussion above, is that it encompasses the greater landscape within which food production is embedded. Foodscape intensity is therefore defined here based on both the intensity of use of the landscape overall, and the intensity of the management system within it. As an index of the intensity of use of the landscape, the report uses the ratio of cropland area to total foodscape area, and for intensity of the management, factors such as nutrient input rates, irrigation and livestock density are considered.

This aggregation yielded three intensity groupings:

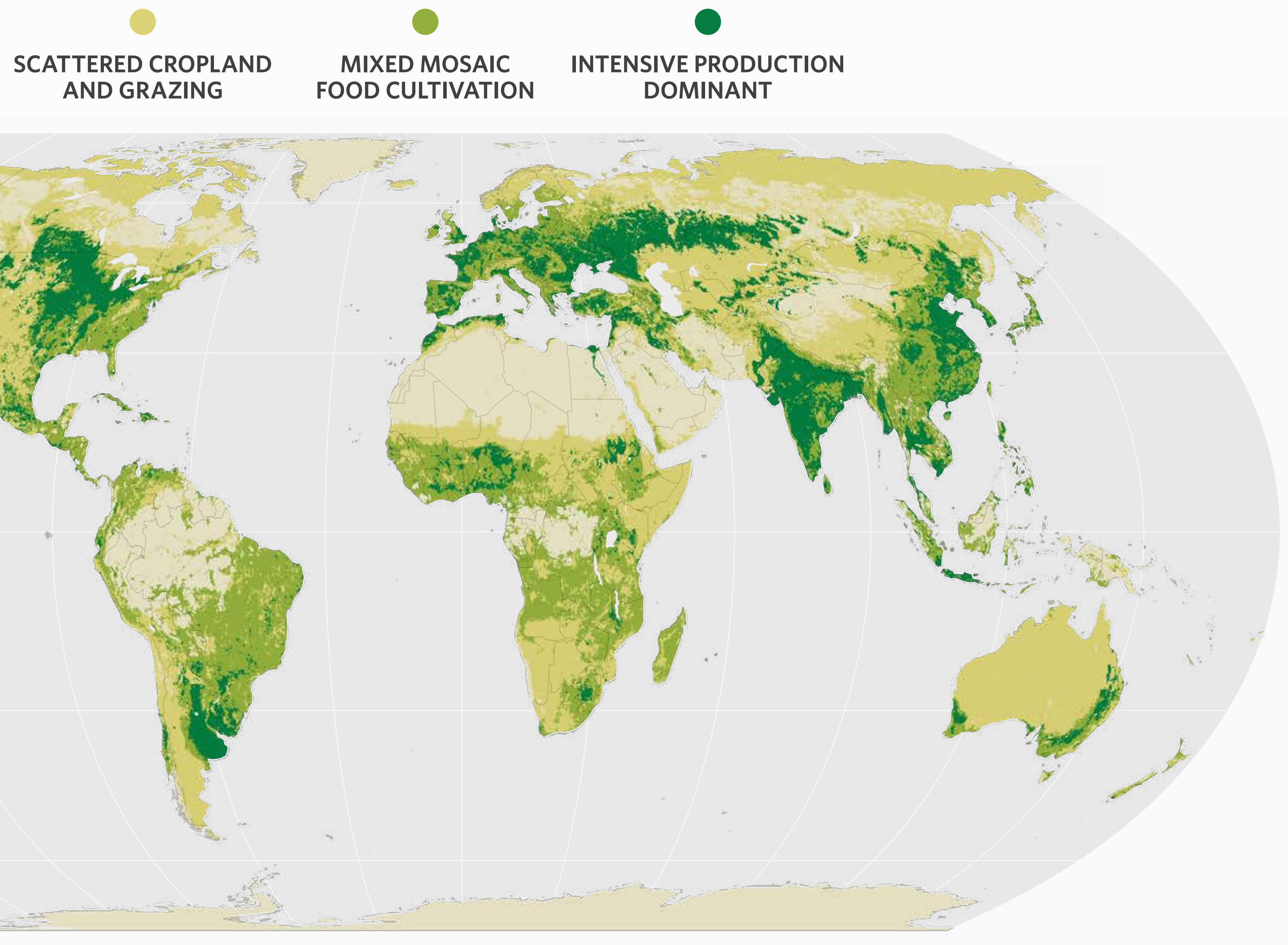
- Intensive production dominant
- Mixed mosaic food cultivation
- Scattered cropland and grazing

The precision of these aggregate groupings should not be exaggerated. It's important to note that aggregations, by definition, often have overlaps among any individual or specific attribute of the different foodscape classes. For example, foodscapes with high nonruminant livestock density, which is increasingly decoupled from crop production due to concentrated confined animal feeding operations, may exist in a class that otherwise fits in the mixed mosaic intensity grouping, rather than the intensive production group. Similarly, classes with small areas of high-input farming, such as small valley bottoms in otherwise hilly landscapes primarily used for grazing or as forest, are grouped with the lower intensity classes given their very small cropland areas.

Crop types including cereals and oil crops, legumes and pulses, tubers, vegetables, perennials, and other crops are distributed across most classes, reflecting that most crops are grown across a range of management systems. Cereals and oil crops tend to be the dominant crops across almost all foodscape classes (FIGURE 3), illustrating the massive dependence of our food system on a few selected crops grown in highly intensified systems.

Approximately half of these crops are used to feed animals or as biomass for energy production (TABLE 1, p.32). Vegetables, on the other hand, are found in a more limited range of foodscape classes, with more than 70% of all vegetable hectares being found in only 12 classes, all of them intensive systems including peri-urban agriculture. Peri-urban agriculture can be of particular importance to local food systems in developing countries where villages and farms intertwine at the landscape scale, and refrigerated transport options are relatively limited.

FIGURE 2. FOODSCAPE INTENSITY GROUP MAP



Distribution of terrestrial foodscape intensity groupings around the world.

FOODSCAPE INTENSITY GROUP DESCRIPTIONS

Group: Intensive production dominant
High potential soils, such as Mollisols found primarily in the world's plains, underpin the majority of the foodscapes dominated by intensive and widespread use of the land area for crop production. This group includes intensive irrigated areas such as the Punjab in Northern India that produces rice and wheat with groundwater irrigation (Punjab-Haryana Foodscape, p.155), as well as the San Joaquin Valley in California, which produces 25% of all fruits, nuts and vegetables consumed in the United States, and is highly dependent on irrigation (San Joaquin Valley Foodscape, p.161).

This intensity grouping also contains foodscapes like those in Russia and Canada that currently support extensive grain production, or like those in the Gran Chaco region of Argentina where demand for soy for animal feed has resulted in the recent conversion of significant areas from dry forest, grassland and wetlands to large-scale cropland (Argentina Gran Chaco Foodscape, p.103). Input rates in these foodscapes can also range from high to moderate, with a relatively high average use rate of almost 120 kg of nitrogen fertilizer applied per hectare per year. These foodscape classes also contain 82% of the world's irrigated farmland.

These are the "breadbasket" foodscapes, both rainfed and irrigated. In their entirety, these intensive-production-dominant foodscapes cover approximately 1.7 billion ha of terrestrial area. Within that area, 753 million acres of cropland produces 65% of gross total global crop output, including 75% of the world's cereal and oil crops. It is important to note that at least half of the outputs from this foodscape group are not used directly for food (see TABLE 1, p.32 and BOX 5, p.36). Within this intensity grouping, overall cropped area averages 38% with some foodscape classes having more than 60% of their area covered in croplands. Livestock density is also highest in these foodscapes, illustrating the close association between crop production and animal production.

Group: Mixed mosaic food cultivation
Somewhat less dominated by croplands and more diverse than the intensive-production foodscapes, this foodscape grouping is comprised of a wide range of soil types and biophysical conditions, often in hilly and mountainous areas ranging from arid to humid. Tree cover can be high and agroforestry systems and plantations are common.

The grouping encompasses a wide variety of farming systems, ranging from Borneo's East Kalimantan, where the tropical forests have been fragmented by oil palm plantations (East Kalimantan Foodscape, p.133), to the Mediterranean where olives and almonds are grown amongst mountainous terrain in Spain (Granada Foodscape, p.139).

Nutrient input rates can range from low to high, as in the Upper Tana River Basin in Kenya, where smallholder farmers grow a variety of tree crops, tea, coffee, vegetables, dairy, and maize, supplying international markets as well as the burgeoning, nearby capitol city of Nairobi (Upper Tana River Basin Foodscape, p.196), or in the Chesapeake Bay where poultry, dairy, silage and feed are the main focus of agriculture, and excess nutrients entering the waterways is an ongoing problem (Chesapeake Bay Foodscape, p.125).

Some foodscape classes within this larger grouping may have very high nonruminant density due to confined animal operations, while the overall average livestock density, nutrient input rates and cropland coverage falls in the middle of the three intensity groups. This foodscape group overall averages 16% cropland cover and produces about 32% of the total global crop output in fresh weight. More than half of the crop output is in perennial crops, such as coconut, oil palm, coffee, tea, cocoa, tropical and temperate fruits, nuts, sugarcane, and bananas.

TABLE 1. CROP BIOMASS USE PER CROP GROUP

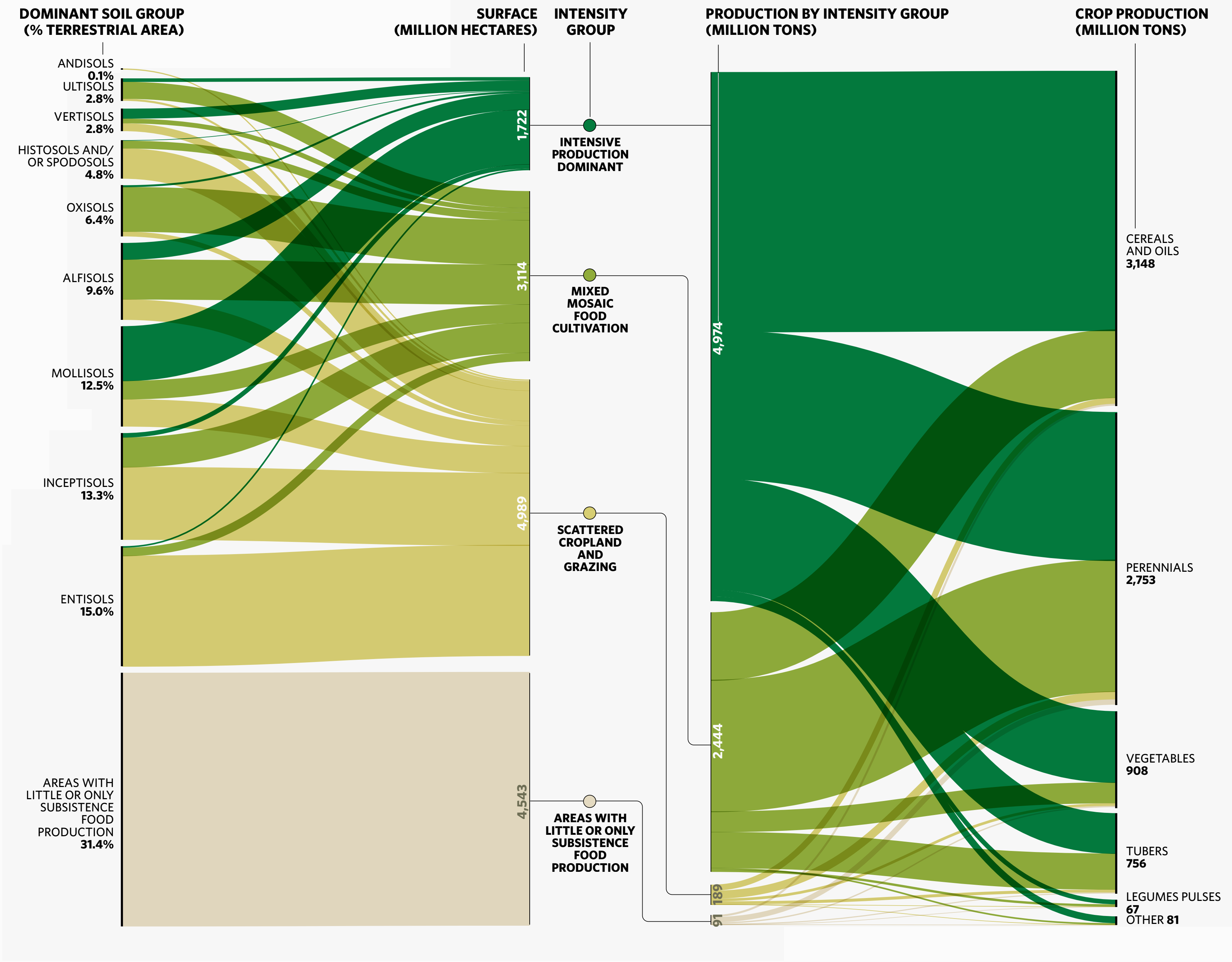
Crop Group	Food	Feed	Losses
Cereals & Oil crops	44%	39%	4%
Perennials	82%	2%	8%
Sugar crops	17%	2%	60%
Tubers	57%	21%	10%
Vegetables	87%	5%	8%
Legumes and Pulses	68%	19%	5%

Data represents the percentage of the harvested fresh matter biomass in different use classes for the dominant crop groups represented in FIGURE 3 according to FAOSTAT Commodity Balance Sheets. Sugar crops (sugarbeets from cereals and oilcrops and sugarcane from perennials), have been separated into their own category for the purposes of this table. Losses are high for sugar crops because they include the fraction of sugarcane non-sugar biomass that may be disposed, recycled to the field, or used as a fuel in refineries.

Group: Scattered cropland and grazing
This large group contains substantial amounts of the world's rangelands and pasture, including large tracts of land that are primarily grazed, such as the steppes of Mongolia (Arkhangai Foodscape, p.111). Cropland area is low here: on average 3% and no more than 10% cropland area are found in the foodscapes of this group. The scattered croplands associated with this group can be either intensive, irrigated grain or pasture; intensive irrigated grain or pasture as found along rivers in semi-arid places like Wyoming in the United States; or scattered low input smallholder farming as in the Niger Delta, where pastoralism is associated with rainfed cereal production and some irrigated rice (Mopti Foodscape, p.147).

While foodscapes in this grouping are associated with animal agriculture, the density (livestock units per hectare of land) of livestock in this group is still far lower than in the intensive food production dominated grouping, the "breadbaskets." However, this scattered cropland and grazing grouping of foodscapes encompasses by far the largest terrestrial production area on Earth — containing just about half the world's foodscape area — covering large areas of North America, South America, Asia, Africa and Australia. Some classes in this grouping have no crop production, and can also extend into areas of tundra in Siberia, Canada and Alaska that have characteristics in common with other places of scattered grazing.

FIGURE 3. GLOBAL FOODSCAPE INTENSITY GROUPINGS AND CROP PRODUCTION



For the purposes of this FIGURE, the Global Foodscape Classes from FIGURE 1 have been consolidated into groupings of similar biophysical attributes on the left side (Dominant Soil Group), and similar management attributes in the middle of the FIGURE (Intensity Group), with total output in fresh weight (Crop Production) of major crop groupings from each foodscape on the right.

FIGURE 3 IN DETAIL

Soil groups identified in figure 3 refer to the dominant soil type found in the foodscape class. Soil type is determined by the complex interaction of parent material, climate, vegetation, terrain, time, and human activity. Foodscapes will thus contain a variety of soil types in complex associations.

Intensity groups identified on the figure are attached to food production areas, and defined based on the areal extent of croplands in the foodscape overall, and the intensity of the management systems within it. Areas with little or only subsistence food production may have some low intensity cropping and grazing, which can be important for local communities.

Crop groups used herein have been established based on the common association of crops in cultivation systems, similarity in cultivation practices, and structural similarities such as the duration of ground cover. The units are tons of fresh weight, and include all crop production, including that which is not used directly for human consumption (see TABLE 1, p.32), but also used for animal feed, energy production and textiles. Animal products are notably missing from this figure. Currently available spatial data did not allow estimation of this important component of foodscape production.

The crop type categories in the figure are as follows:

- Cereals and oil crops include wheat, maize, soybean, rapeseed, rice, barley, pearl millet, small millet, sorghum, sunflower, sesame seed, and groundnuts. This category also includes sugar beet. Many of these crops are grown for both human consumption and as feed for livestock or bioenergy production.
- Perennials are mostly tree crops and shrubs such as tropical and temperate tree fruits, tree nuts, coconut, coffee, cocoa, tea, bananas, plantains and palm crops. Perennials also include sugarcane, which is typically grown for 2-5 years with several cuttings. Within this group, sugarcane accounts for about 65% of the total fresh matter production volume. Yet, only 10% to 15% of the biomass is eventually extracted as sugar (TABLE 1, p.32). Many perennial crops such as fruits and grapes often have water content >80% in their fresh matter, as opposed to <15% in most cereals and oil crops, or legumes and pulses.
- Vegetables include such diverse crops as tomato, lettuces, and many brassicas. Similar to perennials, most harvested crop biomass has a water content of >60% to 70%.
- Roots and tubers encompass potato, sweet potato, cassava, yam and yautia, crops with typical water content >70% in the fresh matter.
- Legumes and pulses are leguminous crops such as lentils, peas or beans that do not primarily serve as oil crops.
- Other crops combine all non-food or feed crops, including fibers and stimulants such as cotton, flax, jute and tobacco.

Fishermen catching anchovies off Hon Yen island in the province of Phu Yen, Vietnam
© Allegra Marcell/TNC Photo Contest 2021

COASTAL SEAFOOD AND MARICULTURE

While our oceans make up over 70% of our planet, they currently provide only 2% of our food. For more than 60 years consumption of fish has been increasing at a rate considerably greater than global population growth; in the period 1961 to 2017 food fish consumption rose from 9.0 kg (live weight equivalent) per person to 20.3 kg.[9] A new assessment of seafood demand and economic trends suggests global demand for fish could double by mid-century.[10]

Historically fisheries have played the fundamental role in supplying fish and fisheries products, and their role continues to be central to food security. In 2018, total fish production (all fish, crustaceans, mollusks and other aquaculture animals but excluding mammals, reptiles, seaweeds and plants) was estimated at 179 million tons, 54% of which came from fisheries and 46% from aquaculture; 52% of fish for human consumption was produced via aquaculture.[9] Yet, if done well, mariculture (the cultivating of marine organisms in our oceans) has the potential to help close the demand-supply gap.

Coastal areas are particularly important, with large- and small-scale coastal fisheries and aquaculture supplying two-thirds of human seafood consumption.[11] Many existing fisheries now have limited capacity to increase production to meet this demand. Furthermore, sustainable growth in aquaculture appears to not be keeping pace, contributing to an increasing seafood demand-supply gap.[12]

Seventy-two million km^2 of ocean appear environmentally suitable to farm one of the 102 most farmed marine species,[13] and 48 million km^2 of currently unfarmed ocean space have been identified as biologically suitable for seaweed farming.[14] A projected 30 times potential increase over current production is considered plausible for bivalve production.[15] Growth in bivalve mariculture in particular has been identified in the FOLU "Growing Better" report as a pathway for realizing greater potential from food systems worldwide.

While this potential exists, the sustainable expansion of mariculture faces constraints, especially technological gaps associated with the availability of sustainable sources of feed. Other constraints include cultural acceptance of mariculture products and effective regulatory guidance.[15] Even where a well-established aquaculture industry exists, many countries lack long-term strategies to sustainably fill this seafood deficit.[16]

Mariculture is also constrained by biophysical factors, including the complexity of farming in offshore, deeper water environments and the role of temperature, salinity and nutrient availability in determining which species can be farmed and how (FIGURE 4). While a wide range of species can theoretically be cultivated in much of the ocean, the majority of current production arises from warmer water environments in coastal waters (<200 m depth), especially in Asia. In cooler water environments where production quantities are high, production tends to be dominated by a small number of species, such as salmonids produced in Europe and South America.

Box 5 Disconnect between crop yields and food production

Crop yield and food production are two different things, and when it comes to understanding the role of various foodscapes in global food production, those differences really matter.

"Crop yield" refers to the mass of a crop harvested per area of land. As such it is an indicator of intensity and efficiency that has been the primary metric of agricultural performance for centuries. And while crop yield, as a gross measure, provides important information about quantities, it does not capture what happens to the crop once it leaves the production unit, whether access to food products is equitable, the quality of food produced, or that alternative systems often produce more than one crop. For example, almost 40% of the cereals and oil crops are used for animal feed and not directly consumed by people (TABLE 1, p.32). In many cases, a crop is used for food (such as soybean oil) and the by-products (such as soybean meal) are then fed to livestock. Overall, 17% of food produced globally is wasted, accounting for around 10% of global greenhouse gas emissions.[2]

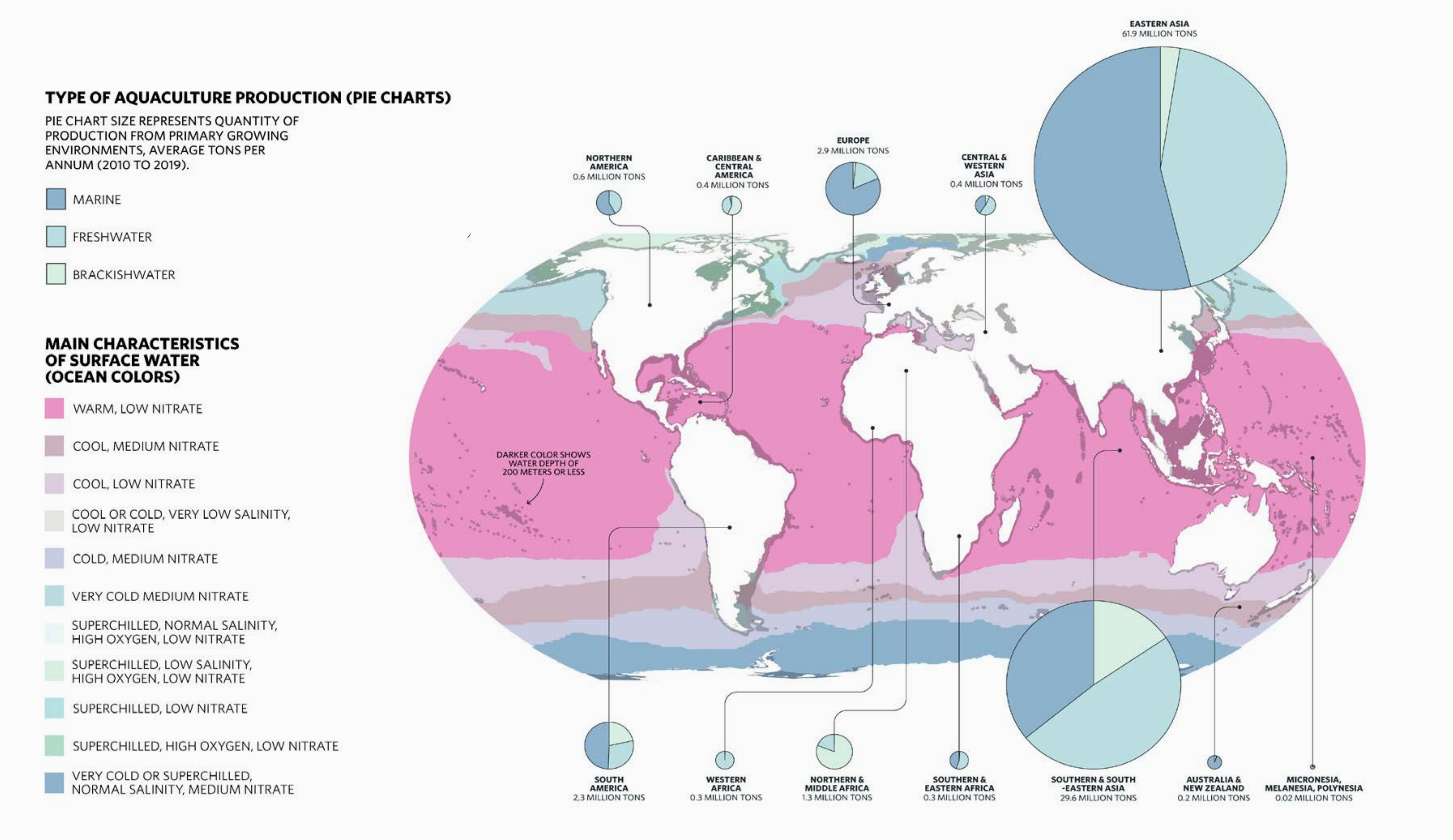
The global food system currently produces — and most countries currently have — more calories and macronutrients (such as protein) available in food supplies for human consumption than are needed for adequate human dietary intake.[3] In other words, despite inefficient use, the world is still in caloric surplus. The challenge, therefore, is not one of caloric yield, but rather nutritional yield[4] and equitable access to food.

To begin to solve this problem, researchers have proposed several metrics to assess the nutritional diversity of food systems.[4–8] In practice, these metrics show that there is not a clear relationship between nutritional diversity of a food system, and what foods are produced by a country. In some cases, countries can focus agricultural production on export commodities and use export revenue to purchase a diverse food supply; in other cases, countries depend on what they produce to provide nutritional diversity in their food supply.[6] As a result, changes in trade patterns – due to policy or vulnerability to global change – can have large impacts on the ability of countries to meet their nutritional needs, with poorer countries being most vulnerable.[3]

A key problem with using yield as a proxy for food production is that it primarily focuses on the efficient production of a single crop. Yet, many nature-based solutions — such as agroforestry and silvopasture —emphasize producing multiple food products from a single parcel of land. Critics of nature-based solutions often focus on evidence of decreased yield for a specific crop, whereas proponents highlight the diversification of food items as a strength.

Right now, it is difficult to make comparisons or account for all the dependencies and nuances of actual food production for human consumption within the global food system. Focusing on holistic measures of food and nutrition, as opposed to the simpler metric of crop yield, is limited by the lack of globally consistent data on the movement, nutritional density, and alternative uses (and waste) of food items. Hopefully, rapid advances in data collection systems will enable consistent and reliable food and nutrition measures in the future.

FIGURE 4. REGIONAL AQUACULTURE PRODUCTION AND CHARACTERISTICS OF THE WORLD'S OCEANS



Average regional aquaculture production (2010-2019) associated with key growing environments. Production quantities represent all potential edible products, including aquatic algae. Main environmental characteristics have been amalgamated for broad representation of common features (of surface waters) in the worlds "ecological marine units."[17]

Total production quantities from the aquaculture industry as a whole are skewed toward output from inland systems. Of the 82.1 million tons (live weight) of fish production from aquaculture in 2018, 51.3 million tons (62.5%) were produced in freshwater environments and 30.8 million tons (37.5%) from marine areas. Production of aquatic algae (predominantly seaweed) occurs largely in marine environments, representing 97.1% of total production (wild-collected and cultivated).[9]

OTHER FOODSCAPES
FOODSCAPE CLASSES OUTSIDE THE CURRENT SCOPE OF THIS ANALYSIS

Ocean Fisheries
Marine wild-capture fisheries provide vital nutrients for more than 3 billion people around the world and serve as a source of income for 10% to 12% of the global population, either indirectly or directly.[18] Food from the sea currently accounts for 17% of the global production of edible animal protein,[15] and wild capture fisheries in particular play an essential role in food security and nutrition by providing critical micronutrients and fatty acids.

Coastal fisheries and small-scale fisheries play a critical role. While the oceans make up 70% of the planet, over 80% of the fisheries harvest comes from the narrow coastal margins that are highly productive and typically have the highest biodiversity.[19,20] Small-scale and coastal fisheries contribute nearly half of the production of all wild capture fisheries, employing an estimated 90% of the world's fishers, mostly in the global South.

These fisheries are located in regions of higher biodiversity when compared with open water ecosystems, such as tropical finfish that inhabit the coral reef ecosystems of Indonesia, or benthic invertebrates such as sea urchins and mussels nurtured by the cool waters of the Humboldt Current off South America's Pacific Coast. Although pelagic species such as tuna and billfishes make significant contributions to the global economy and are essential sources of revenue for small-island states, small-scale and coastal fisheries are the most significant marine contributors to overall global food security.[21]

By 2050, projections for global population growth and income suggest a need for more than 500 megatons (Mt) of meat each year for human consumption — a substantial increase from today's consumption of 360 megatons — and, if managed well, wild capture seafood can continue to provide an alternative to meat. In fact, credible modelling suggests that if all fish stocks were well managed, annual harvest would sustainably increase by 16 million megatons, about one-fifth of current total harvest.[22]

The World Bank estimates that under a recovery scenario, fisheries profits could increase by an estimated $83 billion.[23] The outstanding challenge is to meet increasing fisheries demand sustainably, restoring marine ecosystem function while ensuring that local communities and economies dependent on marine fisheries continue to have secure sources of food and income.

Inland Aquaculture
Aquaculture, in both marine and freshwater environments, is one of the fastest growing food production sectors in the world. As noted earlier, inland aquaculture, which occurs mainly in fresh water, accounted for 62.5% of the world's farmed food fish production: 47 million tons of a total 54.3 million tons.[9] The potential of these systems to support environmental and food security outcomes is high.

Inland integrated rice and aquaculture systems prevalent in places such as Bangladesh and China have been acknowledged for their potential to have lower environmental impact,[24] while simultaneously making positive contributions to food and nutrition security.[25]

Aquatic animals produced through inland aquaculture can have lower resource requirements and an overall lower environmental impact than terrestrial animal agriculture, but these values are highly variable and differ not only between systems but also between species farmed in comparable systems.[26,27] Biodiversity can be affected by inland aquaculture both directly and indirectly. Direct impacts occur through the introduction of non-native species that compete for food and habitat, spread disease, and cause the genetic alteration of wild populations, while indirect impacts are

Drying sardines on the shores of Lake Tanganyika, Tanzania
© Ami Vitale

associated with the modification, conversion, and degradation of existing freshwater habitat.

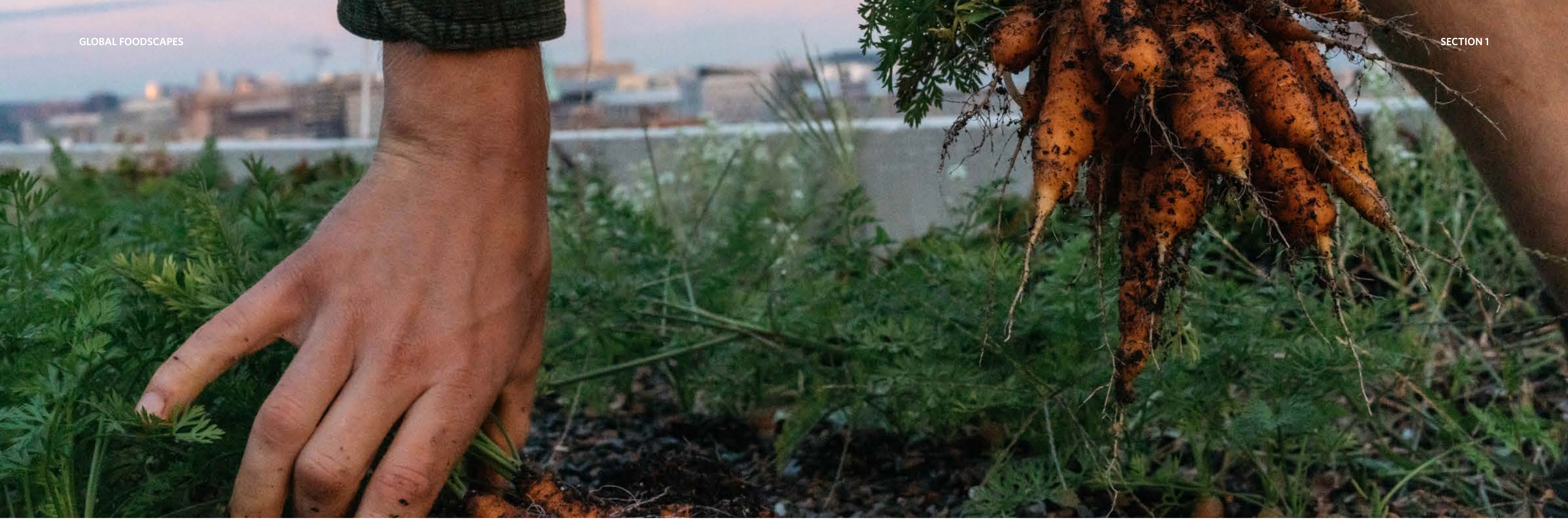
Additionally, inland aquaculture systems can create significant greenhouse gas emissions, including methane. As the demand for food and nutrition produced in aquaculture systems increases, there is an opportunity to address these environmental risks and develop more regenerative systems, such as through greater use of native species and inclusion of catchment management and restoration activities required to ensure water security and resource conservation.

Freshwater Fisheries
Freshwater fisheries are a globally important food source, especially in low-income countries. At least 43% of 11.47 million tons of inland fish production officially reported to FAO in 2015 comes from 50 low-income food deficit countries, providing an amount of animal protein equivalent to the full dietary consumption of at least 158 million people. However, real consumption of freshwater fish is likely to be as much as 60% more than national reports indicate, with at least 90% of reported freshwater fisheries used for direct, local human consumption.[28]

Freshwater fisheries are comparatively low input and low cost. Wild-capture freshwater fisheries leverage the natural productivity of freshwater ecosystems, demanding fewer resources than other food systems, such as aquaculture, intensive agriculture, or livestock production. Floodplains are especially productive, with some locations annually producing >500 kg of caught fish per hectare.[29] Little or no need for inputs means wild-caught fisheries have low carbon footprints. And as fishing can be done with basic tools, it provides an opportunity for communities or individuals to supplement diets or engage in fishing as a last resort.

The consumption of fish, including the bones, eyes, and organs of small species, provides a source of protein that is high in essential vitamins and minerals, many of which are critical for childhood growth and human health.[30] Freshwater fisheries may also enable diet diversification in certain geographies. For example, in areas of sub-Saharan Africa that have historically faced inadequate diet diversity, 20% of children rely on fish from nearby freshwater fisheries as their only source of animal protein.[31]

Forest Products



Harvesting carrots from a rooftop garden, Washington, D.C., USA
© Greg Kahn

Hunting and gathering of forest products is crucial to local livelihoods and diets in many places, and the importance of forest foods in household economies and food security has been promoted by advocates and researchers for decades.[32,33]

A five-country study in sub-Saharan Africa[34] found that an additional forest patch per square kilometer increased the likelihood of consuming fruit by up to 33%. Many of these fruits and vegetables are rich in vitamins and minerals and provide an important nutritional complement to the cereals and tubers that are often cultivated in forested systems. In the East Usambara Mountains of Tanzania, researchers reported that nearly half of all foods consumed were found in forests. These foods contribute more than one-third of human intake of key nutrients such as vitamin A.[35,36] Researchers have found similar results in other forested areas around the world.[37,38]

The viability of these systems is directly related to how they are managed. And that management falls on an extremely broad spectrum between regenerative at one end and extractive at the other. At the extreme end, hunting can lead to a situation where seemingly intact forests are considerably affected by overhunting.[39] There are also crucial linkages between terrestrial and aquatic food systems and the protection of wildlife. In Ghana, years of low fish supply have been shown to lead to large increases in wild meat hunting in wildlife preserves, potentially affecting the sustainability of terrestrial protein sources.[40]

Urban Agriculture

With a majority of the global population living in cities, the role of urban agriculture has potential to become increasingly important in the global food system, even if overall production volumes are likely to remain quite modest.

Urban gardening is found in different forms in cities around the world.[41] This can include gardening in backyards or on vacant plots of land, formally zoned agricultural spaces, and roof-top gardening in high-density environments. Vegetable plots, small animals, chickens, birds and fruit trees are crammed into all available spaces in many urban areas from Brazil to China. In some cases, this food enters into a high-end consumer and restaurant economy, like at Brooklyn Grange — an effort that entails 45,000 kg of produce grown on 2.5 hectares of rooftop gardens in New York City, making it the world's largest rooftop soil-based farm.

Urban gardening also provides a meeting space for community activists and meets food needs in areas with lower access to fruits and vegetables. The D-Town Farm in Detroit, Michigan is a 3-hectare farm that also organizes lecture series, youth development programs, and a food co-op that allows members to buy healthy food at below-market prices.

For many, urban food production is intricately linked with environmental and food justice. In Freetown, Sierra Leone, the government has zoned low-lying valleys in the city for urban agriculture to reduce flooding and promote food supply. The city government of Toronto, Canada is providing financial support to urban agriculture as part of its climate mitigation plan because it is thought urban agriculture can reduce shipping distance.

Some urban agriculture efforts have a strong technological focus, from lab-based synthesis of proteins to vertical farming and the growing of vegetables in controlled environmental facilities and/or with hydroponic technologies and practices.

Urban agriculture has become such a strong feature of the urban environment that the American Planning Association now provides specific guidance on how to incorporate urban agriculture into urban planning through tax incentives, zoning policy, and land development codes.[42] The US Centers for Disease Control includes information on urban agriculture as part of its healthy foods guidance.[43]

Corn ready for harvest near the Missouri River, USA © Dan Videtich

SECTION 2

The State of Our Foodscapes

The world's foodscapes have supported a steady increase in food production during decades of population growth and dietary evolution. Yet there are considerable headwinds. Climate change and associated natural disasters—drought, fire, flooding, and pest and disease outbreaks—threaten the resilience of the world's foodscapes.

THE STATE OF OUR FOODSCAPES

At the same time, the ways in which we manage—or mismanage—foodscapes has multiple impacts on food production and the environment. Food production is paradoxical: it depends on a healthy environment but is simultaneously a strong driver of environmental degradation.

Land conversion and use of the sea degrade natural habitat, threaten biodiversity, release carbon into the atmosphere, and undermine the multiple ecosystem services that flow from natural habitat such as pollination. Overexploitation of natural resources, including soils and water, compromises the long-term productivity of foodscapes. Overexploitation of bushmeat and other wild game and fisheries has led to empty forests and seas and even launched zoonoses that threaten future pandemics.

Pollution (e.g., heavy metals) renders land unproductive and degrades water quality that wild and managed fisheries rely on. Overuse of water and pollution from nutrients, sediment, and pesticides threaten aquatic biodiversity and the security of our water resources.

In this section the relationship between various pressures on the environment and foodscapes is explored.

The analysis is organized around four types of pressures that encompass drivers with the largest impacts on biodiversity:[1]

- land/water/sea use change
- resource exploitation
- climate change
- pollution

It also examines how food production is both subject to, and responsible for, environmental degradation, including loss of biodiversity and ecosystem services, within the world's foodscapes.

While data sets are not as extensive for marine foodscapes, this report also draws on published research to examine pressures there as well. Recognizing the accelerating nature of the challenges and the need to rapidly transform the global food system, the report calls for an integrated set of interventions to regenerate foodscapes, sustain food production, and protect biodiversity.

TERRESTRIAL

LAND USE CHANGE

Conversion and fragmentation of native habitat for food production comes at a cost to the environment. Conversion, degradation and fragmentation of native habitat for food production and related economic activity comes at a cost to the environment, and is the greatest threat to terrestrial biodiversity.[2] It is important to note that terrestrial land use changes can and do have profound effects on marine and freshwater biodiversity as well.

Ironically, perhaps, expansion of our food production footprint can also undermine the productivity of the foodscapes themselves by damaging the ecosystem services that underpin that productivity in the first place.

For example, 70% of leading crops are wholly or partially dependent on animal pollinators for crop pollination.[3] Similarly, natural pest predators, like parasitoid wasps, provide biological pest control when suitable habitat, such as the native plants they prefer, is interwoven into agricultural land. While currently less well understood, soil communities mediate the biogeochemical cycling that enables crops to access essential nutrients.[4]

Agrobiodiversity, especially wild crop relatives, provides genetic resources that can be tapped when foodscapes face new sources of biotic and abiotic stress.[5] These genetic reserves are especially critical given the intense selection pressure facing many cropping systems, which lead to rising rates of pesticide resistance and disease susceptibility. Genetic diversity will only become more urgent as climate change exacerbates pest and disease pressure in many of the world's most productive foodscapes.[6]

This analysis examines the relationships between land use changes and foodscapes by examining where and how foodscapes intersect with three indices of change and biodiversity, namely:

- critically endangered ecosystems,
- areas of high species conservation value, and
- frontier expansion zones.

Critically Endangered Ecosystems

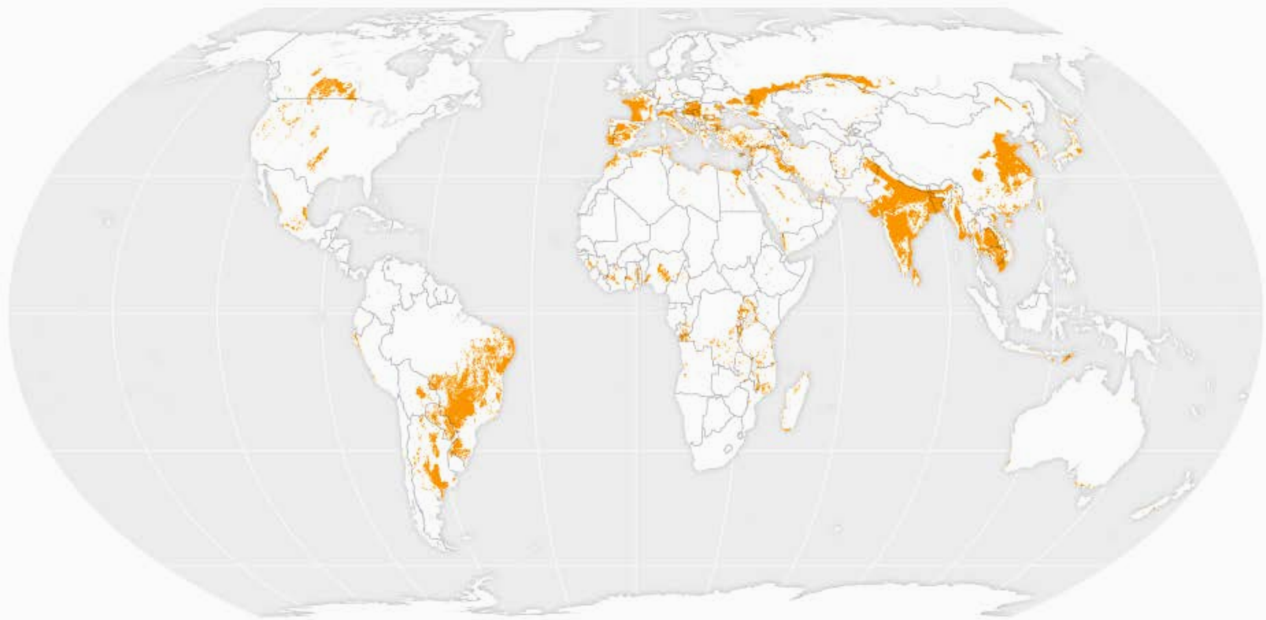
Critically endangered or crisis ecosystems are defined as foodscapes where a high proportion of native habitat has been converted for food production (>80% converted) and where the least amount of remaining habitat area is formally protected (<10% protected) (FIGURE 5). The foodscapes most affected, both in total area and proportion of area, are some of the world's most intensive systems, such as the North China Plain, parts of the Brazilian Cerrado, the Canadian Prairies, the Pontic-Caspian Steppe, and the Indo-Gangetic Plain.

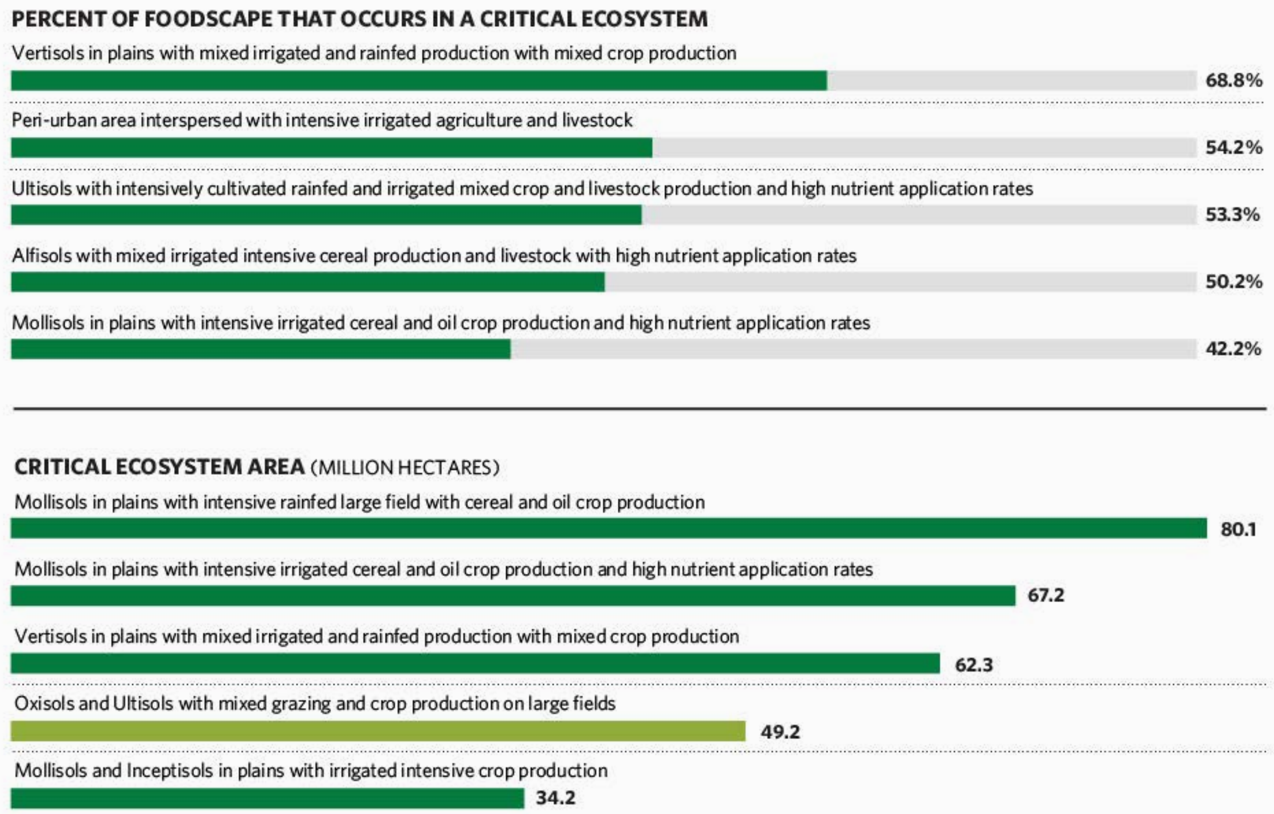
In these foodscapes, biodiversity conservation can be advanced through expanding protected areas, restoring habitat in marginal areas of production and areas of high conservation value, and integrating habitat and agrobiodiversity into existing production lands. The challenge is daunting, since many of these areas are highly productive "breadbasket" foodscapes with significant opportunity costs for conservation. Nevertheless, since their high output makes them particularly important to the world food system, the costs of business as usual will be even higher if productivity is compromised by environmental damage.

Without broader shifts in demand, reducing production in these areas has the potential to lead to leakage, where less productive land elsewhere is placed into production to compensate and maintain yields. These challenges are explored further in the Punjab-Haryana foodscape Brief (p.155).

SEE FIGURE 5

FIGURE 5. FOODSCAPES AND CRITICALLY ENDANGERED ECOSYSTEMS





Global distribution of critically endangered ecosystems, defined as ecosystems with low levels of protection (<10%) and high levels of native habitat loss (>80%). Bars indicate foodscape classes with the highest proportion of land affected and the largest areas affected by the pressure. The color of bars indicates the intensity groupings: intensive production dominant (dark green); mixed mosaic food cultivation (light green); scattered cropland and grazing (yellow).

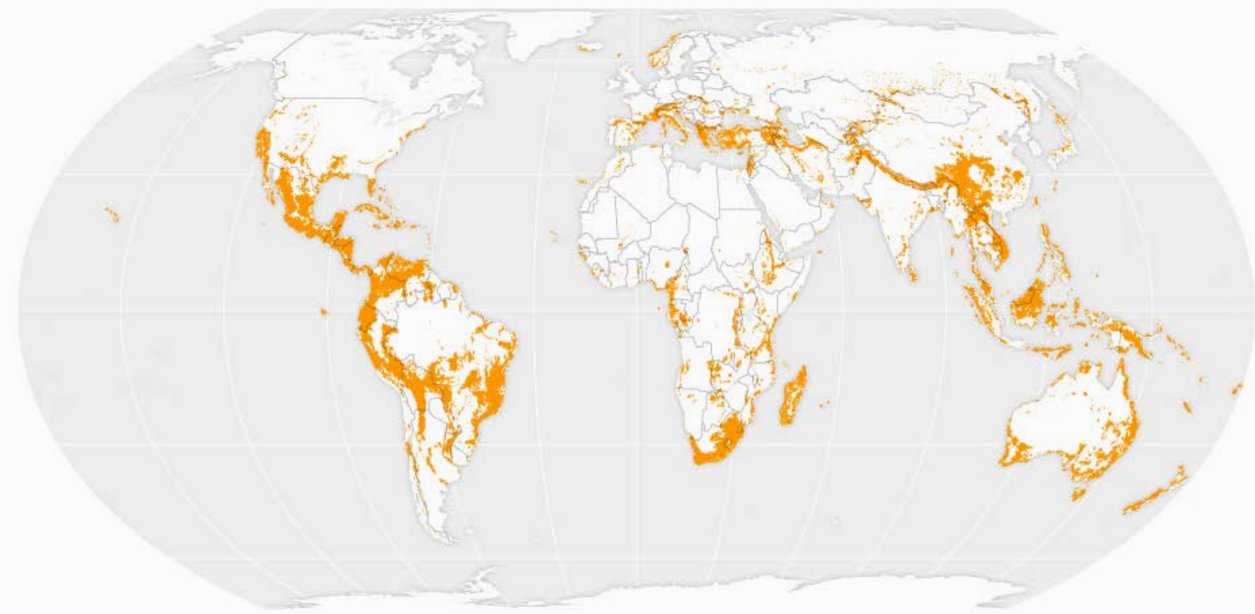
Areas with High Conservation Value

An alternative perspective on the intersection between food production and conservation is provided by a new dataset that identifies and ranks areas by their value in reducing species extinction risk if those areas are carefully managed or protected.[7] Sub-setting this new dataset to focus on the 10% of land with the highest priority ranking (FIGURE 6) paints a different picture than a focus on critically-endangered ecosystems alone. It emphasizes less intensively cultivated foodscapes that include hotspots for endemism such as the Andes, Mesoamerica, South Africa, the Atlantic Forest of Brazil, and the highlands of southeast Asia.

These foodscapes tend to be hilly or mountainous and often support large populations of smallholders, presenting opportunities to support a larger number of livelihoods, address equity issues, and promote integrated production systems that take advantage of the high levels of agrobiodiversity typical in many smallholder landscapes. These opportunities are discussed further in the Upper Tana River Basin foodscape Brief (p.169).

Daily farm work of Vietnamese farmer
© Van Nguyen/TNC Photo Contest 2021

FIGURE 6. FOODSCAPES AND AREAS TO PROTECT WITH HIGH CONSERVATION VALUE



TOP 5 FOODSCAPES BY PROPORTION AFFECTED

Inceptisols on humid mountaineous land with tree cover and scattered mixed crop production	43.6
Inceptisols on humid hilly-mountains with tree cover and small farmed mixed and intensive diverse production	43.6
Ultisols on hilly and mountainous tree-covered land with diverse crop production and high nutrient application rates	42.8
Andisols on hilly and mountainous land with sparse crop production and ruminants	40.4
Oxisols and Ultisols on humid hilly tree-covered land with agroforestry and some livestock	38.5

TOP 5 FOODSCAPES BY AREA AFFECTED (MILLION HECTARES)

Inceptisols on humid hilly-mountains with tree cover and small farmed mixed and intensive diverse production	107.7
Mollisols in mountaineous-hilly areas with low density livestock grazing and scattered crop production	80.1
Oxisols and Ultisols on humid tree-covered land with diverse small field production and agroforestry	74.4
Inceptisols on humid forested hills with intensive mixed crop production and grazing	65.0
Entisols on plains with bare land and scattered mixed crop production and low nutrient application rate	64.3

The 10% of the earth's land surface that, if protected, would avert the greatest loss to threatened and endangered species. Bars indicate foodscape classes with the highest proportion affected and the largest areas affected by the pressure. The color of bars indicates the intensity groupings: intensive production dominant (dark green); mixed mosaic food cultivation (light green); scattered cropland and grazing (yellow).

Agricultural Frontier Zones

Food production remains the leading cause of habitat conversion. To understand patterns of land conversion, this analysis draws on a global dataset of landcover change between 1992 and 2015[8] to identify the areas where native habitat was converted for use as cropland and grassland (FIGURE 7). Many of the foodscapes experiencing significant land conversion during this period are lower intensity, arid or cold regions that were previously not considered prime arable land.

Hotspots include the African Sahel, the Russian boreal forest, the Brazilian Cerrado, the Argentinian Chaco, coastal Maghreb, and central Australia.

Land conversion in arid and semi-arid foodscapes may be overestimated due to challenges using remote sensing to monitor change in these landscapes. On the other hand, more recent expansion in the Cerrado and Amazon is not represented in this dataset; similarly, conversion to forest plantation (e.g., for oil palm) in Indonesia and Malaysia is likely underrepresented. Landscapes that experienced extensive land conversion in earlier periods (e.g., the United States, Europe, India, China) are not captured in this analysis.

Advances in agronomic practices and technology have opened up new agricultural frontiers in places like the Chaco and Cerrado, and livelihood pressures have placed increased strain on native habitat in regions such as the Sahel, Central Asia, and southern Africa. Success in reversing these trends will require carefully developed policy as well as alternative economic development alternatives for the rural poor. This is explored in greater detail in the Argentina Gran Chaco foodscape Brief (p.103).

Resource Exploitation

Resource exploitation directly linked to food production — which includes river and groundwater abstraction for irrigation, soil erosion and degradation, and harvesting of wild game and plant products — can have a complex but significant impact on biodiversity and ecosystem health and at the same time undermine the long-term sustainability of food production.

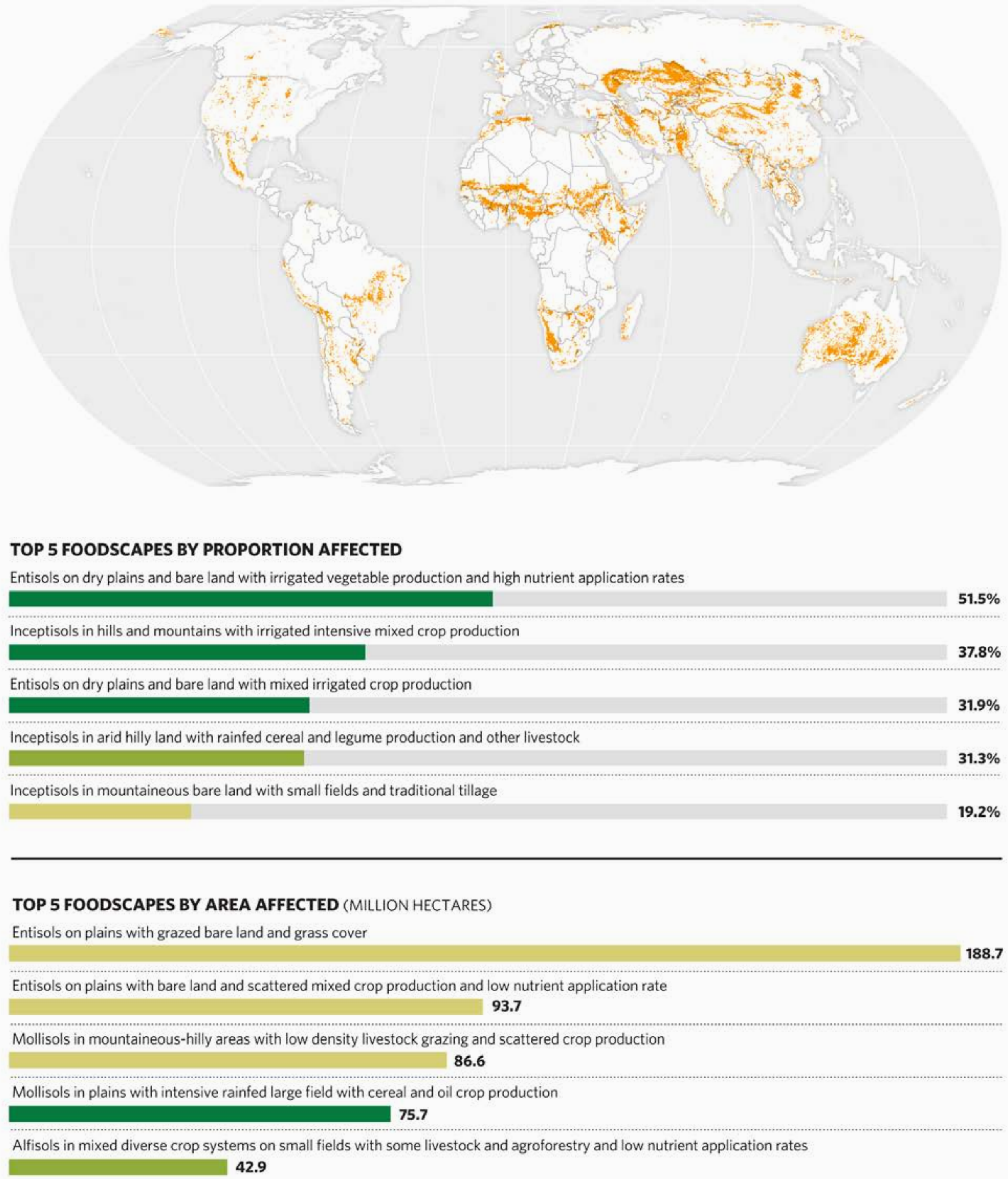
Previous analysis in Section 1 highlighted the outsized role areas with both highly fertile soils (like the Mollisols common in the Intensive group) and abundant rainfall or access to irrigation play in supplying the world's crops and livestock. With few exceptions (for example, controlled-environment aquaponics), food production depends on natural resources such as healthy soil and access to fresh water, as well as services provided by specific ecological communities (pollination, pest predation, biogeochemical cycling, etc.). Over exploitation of water resources can affect the productivity and health of inland and coastal fisheries by reducing the base flows necessary to both sustain aquatic biodiversity and flush pollutants from water bodies.[9] Soil erosion and degradation often damage water and air quality while simultaneously undermining the ability of a landscape to support food production and other critical ecosystem services, such as carbon sequestration.

In addition, overexploitation of wild game and plant products can have complex but significant impacts on biodiversity and ecosystem health, and at the same time undermine the long-term sustainability of food production. Forests and rangelands face a considerable threat from the over harvesting of native species as a source of food (hunting, fishing, foraging).[10] A few foodscapes that appear globally marginal for food production – particularly tropical forests – face considerable pressure from unsustainable harvest of wild species as food.

This analysis examines where and how foodscapes are affected by two aspects of resource exploitation directly linked to food production:

- soil erosion
- water scarcity

FIGURE 7. FOODSCAPES AND AGRICULTURAL FRONTIER ZONES



Global distribution of areas that experienced an expansion in crop and rangeland between 1992 and 2015. Bars indicate foodscape classes with the highest proportion affected and the largest areas affected by the pressure. The color of bars indicates the intensity groupings: intensive production dominant (dark green); mixed mosaic food cultivation (light green); scattered cropland and grazing (yellow).

Soil Erosion

Soil erosion is a chronic problem that has plagued agricultural and grazing land worldwide for centuries. Soils form slowly — over millennia — and store an estimated 80% of the carbon in the biosphere. Yet many soils are still managed poorly: overgrazing, excessive tillage, bare fallow, salinization, poor nutrient management, and other factors impair soil health and function, and exacerbate soil loss from erosion.

Globally, more than one-fifth of the total land area, and more than half of all agricultural lands are now degraded. Agricultural land uses over the last 12,000 years have resulted in the astounding loss of 116 gigatons of carbon from soil globally.[11] Healthy soils can sequester carbon – helping mitigate climate change – and support more resilient food production systems because, among many other benefits, good soil structure and organic matter content improve soil's ability to absorb and retain rainfall.

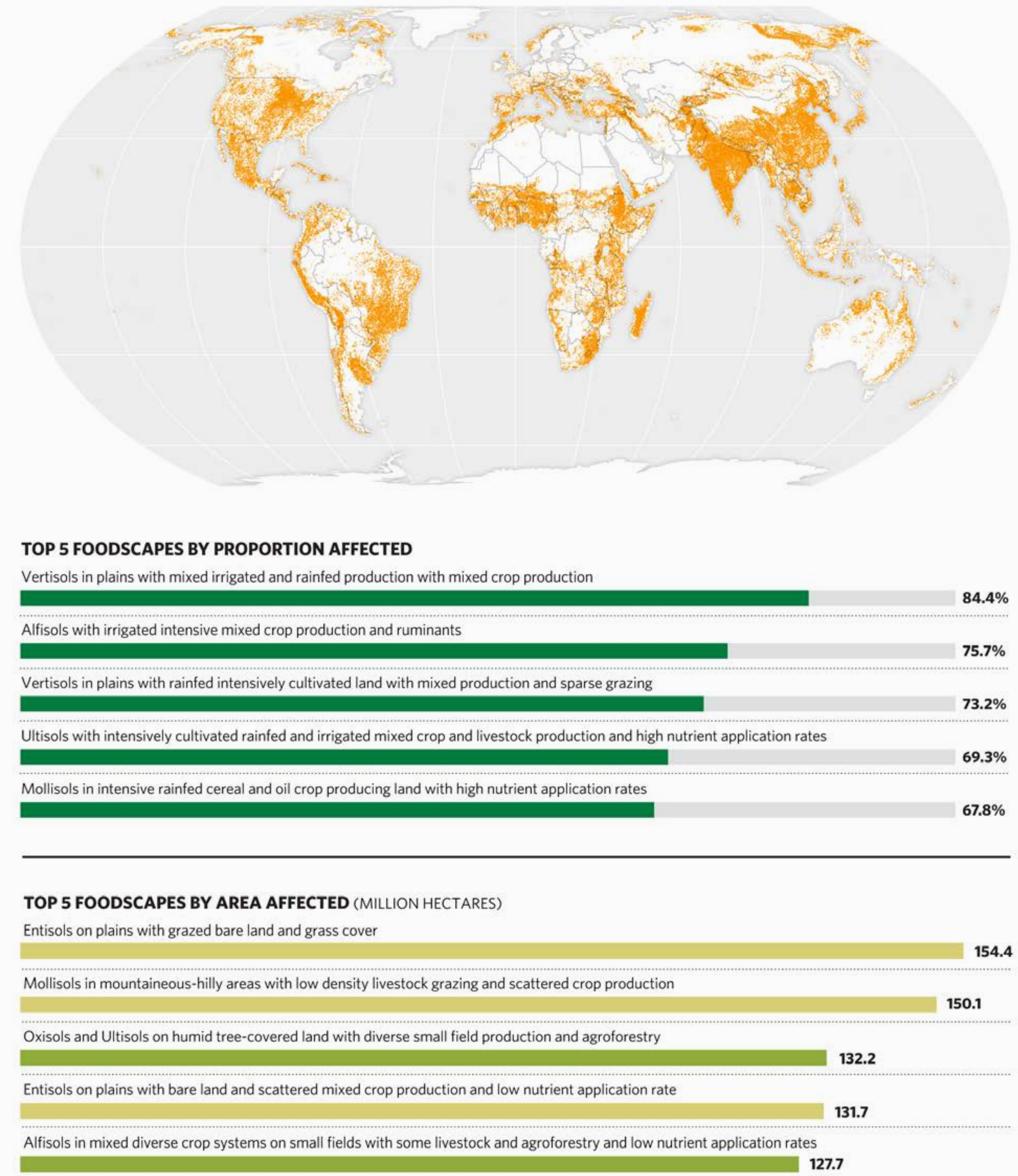
Here, the analysis examines one broadly applicable indicator of soil degradation — soil loss caused by water erosion. To identify high-risk areas for water erosion, the foodscapes map was overlaid with a dataset that estimates erosion volumes using the Revised Universal Soil Loss Equation.[12] Locations showing the greatest (top 25%) estimated soil loss from water erosion were identified as high-risk areas (FIGURE 8).

It is important to note that most of the planet's agricultural lands end up highlighted as "at risk" because of the extent to which agricultural production exacerbates erosion. Soil erosion rates from water in agricultural lands are typically at least one or more orders of magnitude higher than those that occur under native vegetation.[13] Some of the highest rates of erosion occur in intensively cultivated landscapes such as the midwestern United States, southern Brazil, Bangladesh, and large parts of eastern China.

While not analyzed here, wind erosion can also affect foodscapes, especially those in arid and semi-arid regions. Even without wind or water erosion, soil can still be degraded. Agricultural practices that disrupt soil structure and fail to provide organic material inputs will cause loss of soil organic matter and its associated carbon, and degrade water and nutrient cycling processes.

Practices that reduce soil disturbance and increase vegetative cover, including reduced tillage, cover/intercropping, agroforestry, and crop residue conservation/mulching, can help mitigate many causes of erosion, especially water. Unsurprisingly, the less intensively cultivated but hilly and mountainous areas of Peru, Ethiopia, India and the Himalayas are also erosion hotspots. Cultivation of steep slopes can lead to extreme erosion rates, although many techniques have been developed to help mitigate erosion in smallholder settings where cultivation of steeper and more marginal land is largely unavoidable due to livelihood needs.

FIGURE 8. FOODSCAPES AND SOIL EROSION RISK



Global distribution of land areas featuring a high (upper quartile) rate of soil erosion due to surface runoff. This includes nearly all of the world's cropland. Bars indicate foodscape classes with the highest proportion affected and the largest areas affected by the pressure. The color of bars indicates the intensity groupings: intensive production dominant (dark green); mixed mosaic food cultivation (light green); scattered cropland and grazing (yellow)

Water Scarcity

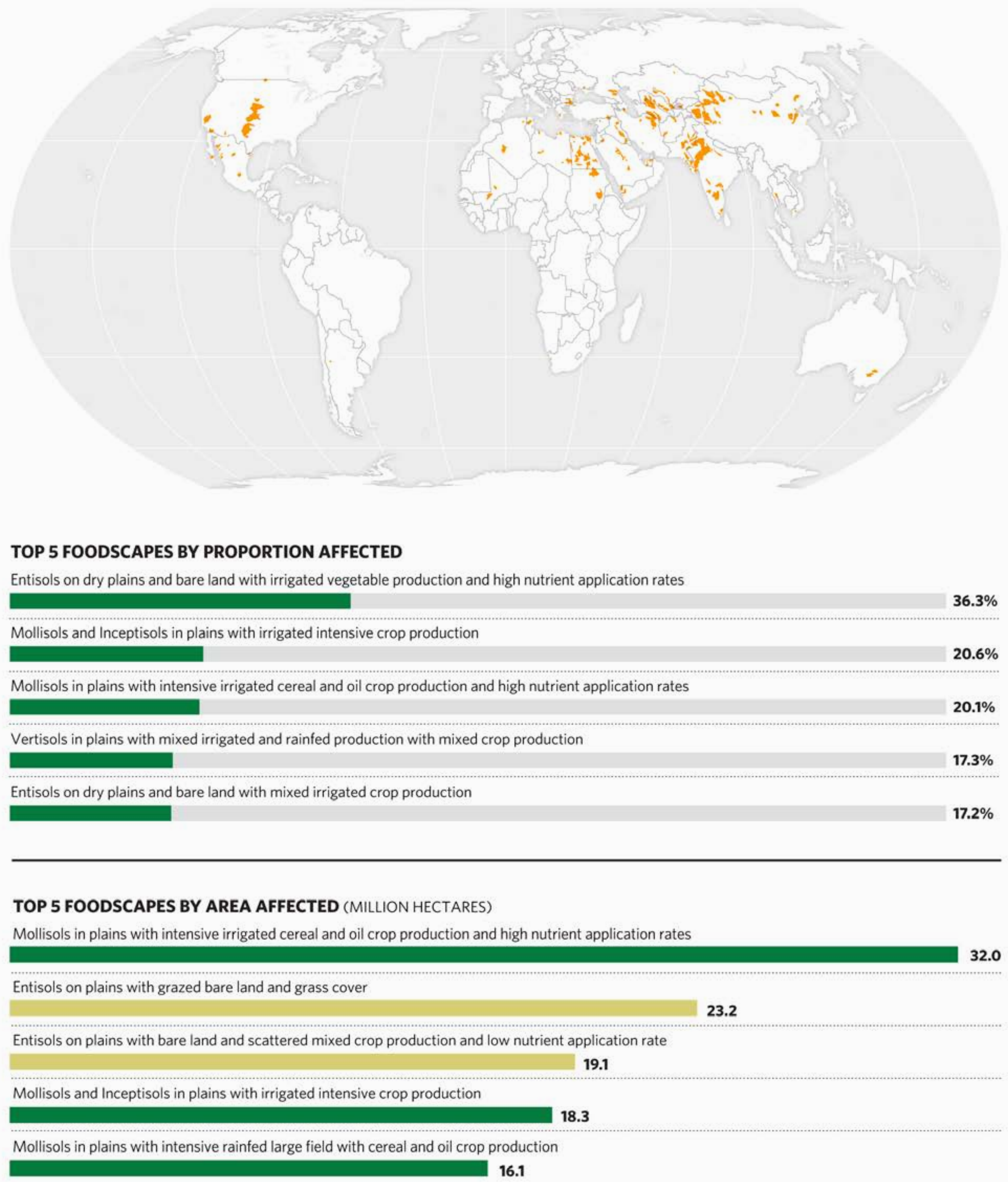
Globally, over 70% of available fresh water, from both surface and groundwater sources, is used for agricultural irrigation and food production in general. In places such as India, Peru, and many countries in the Middle East and North Africa, the share of water used for food production reaches nearly 90% of available supplies. While rainfed production systems typically have crops and management practices at least partly adapted to the seasonal availability of water, climate change will disrupt typical seasonal cycles, in addition to increasing the frequency and intensity of droughts and floods.

To identify foodscapes already at significant risk from existing water scarcity, the foodscape classes were overlaid with a map of areas that are 75% or more water depleted drawing on the global WaterGAP dataset. This identifies areas of extreme concern for water depletion.

Areas at the greatest risk fall into two foodscape groupings (FIGURE 9). The first are intensively cultivated and irrigated regions that often currently depend on unsustainable groundwater extraction (for example, the Ogallala basin in the US Great Plains, the Central Valley of California, the Punjab in northwest India and Pakistan). The second, representing larger areas affected, are arid, rainfed cropping systems in Central Asia and North Africa that cannot sustain intensive production.

Many irrigated systems face long-term risks due to excessive abstraction of ground and surface water for irrigation. Managing overstretched groundwater resources is a complex collective action problem explored in greater detail in the San Joaquin Valley Foodscape Brief (p.161).

FIGURE 9. FOODSCAPES AND WATER RESOURCE DEPLETION



Global distribution of areas that are already 75% or more water depleted, as estimated using the WaterGAP dataset. Bars indicate foodscape classes with the highest proportion affected and the largest areas affected by the pressure. The color of bars indicates the intensity groupings: intensive production dominant (dark green); mixed mosaic food cultivation (light green); scattered cropland and grazing (yellow).

CLIMATE CHANGE

The food system is responsible for as much as 35% of global greenhouse gas emissions, with most coming from land conversion, enteric fermentation from livestock, fertilizer production and application, flooding for rice production, logistics, and food processing.[14] The factors driving emissions are not uniformly distributed.

Livestock systems are increasingly dominated by intensive confinement or semi-confinement operations, often concentrated in specific geographic regions (e.g., the US Midwest, the Netherlands, northern China, etc.). This concentrates emissions as well as nutrients in the form of manure. Similarly, flooded rice production occurs in only a few parts of the world.

While emission rates may vary, ultimately all sources of emissions mix and drive planetary-scale warming. The effects of climate change from all causes on food production are local and varied; some foodscapes are far more vulnerable than others to extreme weather and changing pest and disease dynamics, among other factors.

This analysis explores the relationship between foodscapes and climate risk using a new global dataset of current and future climate risks to food production.

Climate Change Risks

Extreme weather events (drought, flooding, temperature anomalies) threaten food production and can make field management difficult, hazardous or impossible. Agricultural workers, for example, are directly exposed to the effects of extreme heat, and climate also affects pest and disease dynamics.

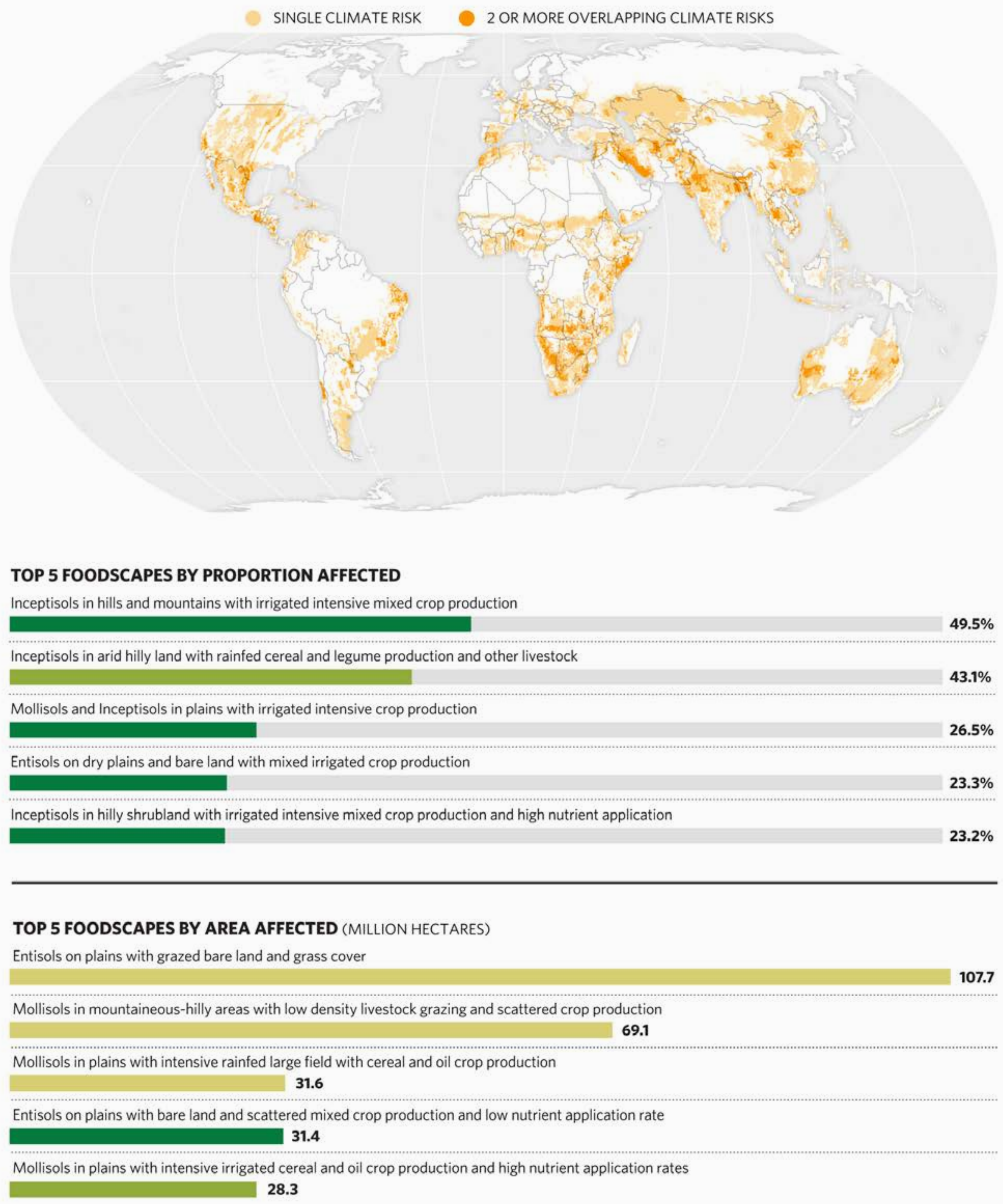
To explore the risks global climate change holds for food production within the world's terrestrial foodscapes, this analysis uses a recently created data layer identifying hotspots for global climate risks:[15]

- flooding
- drought
- climate variability
- high growing season temperatures
- reductions in the growing season

The first three risks are assessed for current-day conditions, whereas the latter two risks are projections to 2050. Researchers identified areas that face no risks, one risk, or multiple risks (FIGURE 10).

The foodscapes most affected by proportion of their area are primarily those in the intensive grouping including our breadbasket foodscapes. The areas facing multiple climate-related risks include large parts of Iran, Bangladesh, northwest India, eastern Mexico, and several regions in southern Africa and Australia. Many of these regions include significant populations of smallholders, some of whom are already exposed to challenges such as heat and drought.

FIGURE 10. FOODSCAPES AND CLIMATE CHANGE RISK



Global distribution of areas exposed to risk from one or more climate change-related hazards. This includes present-day risk and projected risk in 2050 (source data). Bars indicate foodscape classes with the highest proportion affected and the largest areas affected by the pressure. The color of bars indicates the intensity groupings: intensive production dominant (dark green); mixed mosaic food cultivation (light green); scattered cropland and grazing (yellow).

POLLUTION

Largely because of the ways they're managed, foodscapes can be significant sources of pollution. On land, the application of fertilizer, manure, herbicides and pesticides can lead to runoff that impairs water bodies, causing eutrophication and areas of extreme hypoxia ("dead zones") and other effects.[16] In turn, sediment pollution caused by erosion from tillage, cultivation of steep slopes, bare fallow, or other practices can compound these effects, while also impairing the functioning of downstream hydropower facilities and other infrastructure.

Pesticide use in agriculture has risen sharply over recent decades, and globally more than 4 million tons of pesticides are used every year to manage pests, weeds, and disease.[17] Pesticides can also directly impact off-target species, including humans, due to misapplication, trophic effects, and mobility in water and soil.

Just as food production can cause pollution, it can also suffer from it. Poor soil and irrigation management can lead to salinization of soils, rendering them infertile. And because crops are a reflection of their environment, heavy metals, persistent organic pollutants, and other toxins can render crops unsafe to consume.

This analysis examines where and how foodscapes are affected by one important form of pollution directly linked to food production, nitrogen pollution.

Nitrogen Surpluses

Nutrient pollution is a threat to people and nature, and directly links terrestrial and aquatic ecosystems. Nitrogen, in particular, is highly mobile in the environment, and whether from manure or applied as fertilizer, nitrogen easily leaches into waterways or enters the atmosphere. While the factors that govern the nitrogen cycle are complex and heterogenous in time and space, the nitrogen balance on a field is a good proxy for the likelihood of losses to the environment.[18]

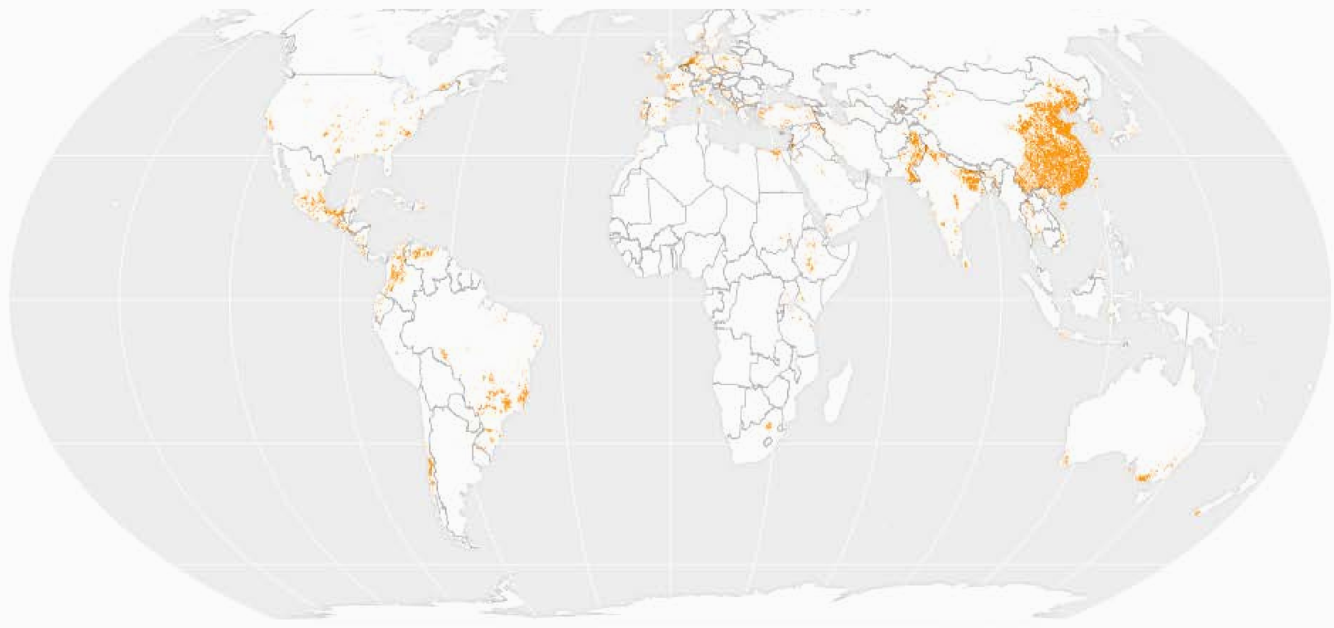
The nitrogen balance is the sum of all nitrogen added to a particular field over the course of the year (including biological nitrogen fixation e.g., by legumes), minus the amount removed by the harvested crop. A well-managed farm should have a nitrogen surplus — some losses to the environment are inevitable — but large surpluses are usually an indication that excess nitrogen is being applied and lost to the environment as pollution.

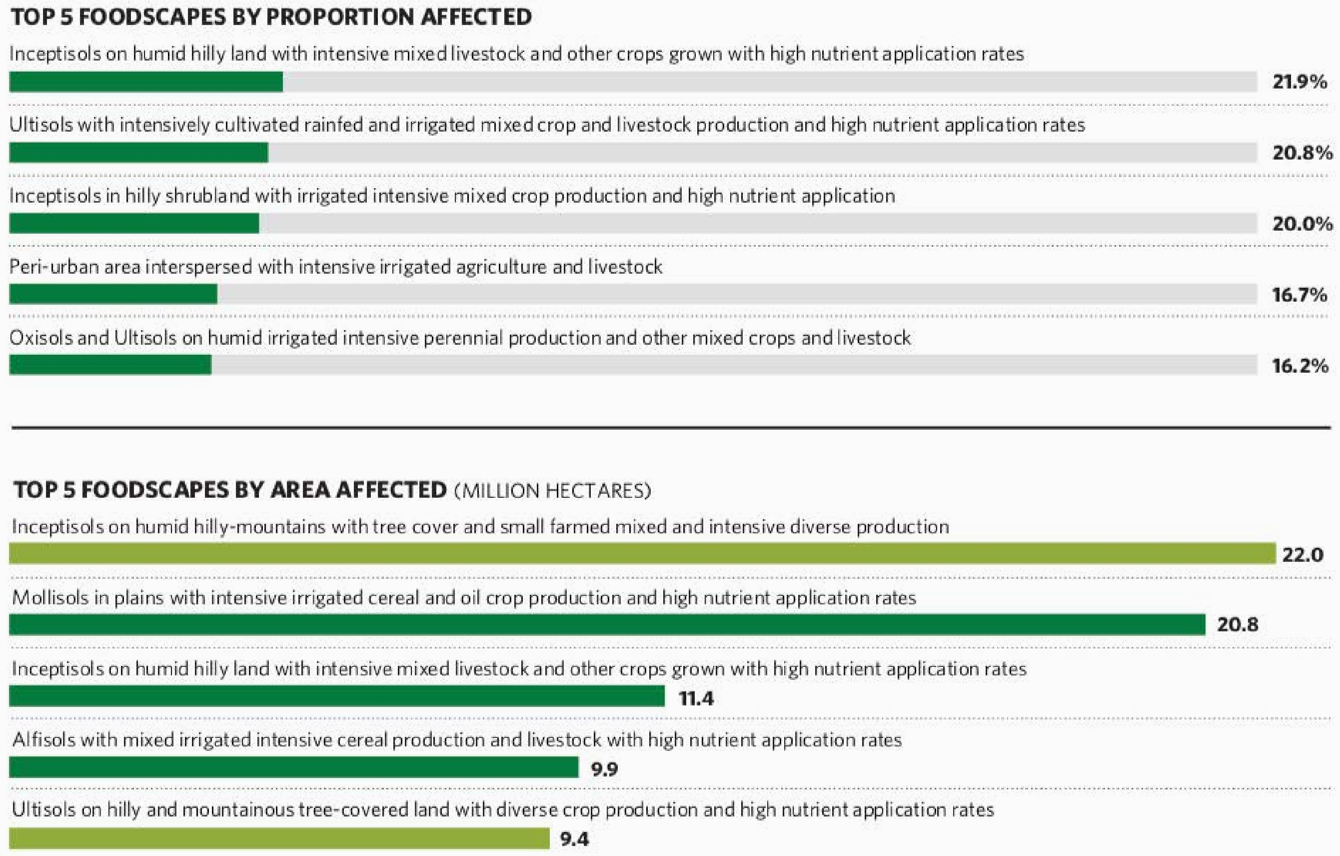
To identify food production areas with high nitrogen surpluses, multiple datasets were combined to estimate nitrogen balances across croplands, grazing lands and livestock operations in the world's terrestrial foodscapes.[15] A particular challenge in determining nitrogen balances is accurately accounting for manure, which globally contains more nitrogen than is applied annually as synthetic fertilizer,[18] and so areas with dense livestock populations can be a major driver of nitrogen surpluses.

Much of this manure is deposited on grazing lands, replacing nitrogen removed by grazing or browsing. However, in intensive grazing systems, such as dairies in New Zealand and Ireland, nitrogen deposition in pastures can be an important source of nitrogen pollution in the wider environment. In systems where animals are confined either partly or entirely, a large portion of the manure can be captured, stored and applied to fields as fertilizer.

This analysis highlight several regions with significant nitrogen surpluses. Eastern China is a hotspot for surplus nitrogen due to both high fertilizer use and livestock density. The Indo-Gangetic Plain, parts of South and Central America (Colombia, Ecuador, southern Brazil), and coastal areas in north-central Europe (e.g., the Netherlands) also stand out for their significant nitrogen surpluses, which can be expected to pose pollution challenges for fresh water (including groundwater) and coastal marine ecosystems.

FIGURE 11. FOODSCAPES AND NITROGEN SURPLUS





Global distribution of areas with high nitrogen surpluses (top quartile), which equates to surpluses greater than 87 kg ha^{-1}. Bars indicate foodscape classes with the highest proportion affected and the largest areas affected by the pressure. The color of bars indicates the intensity groupings: intensive production dominant (dark green); mixed mosaic food cultivation (light green); scattered cropland and grazing (yellow).

Aquaculture near Ly Son Island, Vietnam
© Alex Cao/TNC Photo Contest 2021

MARINE

HABITAT LOSS

Food production in the world's marine foodscapes depends on a healthy environment and intact habitat. Habitats such as kelp forests, coral reefs, and mangroves serve as nurseries for wild fisheries and also provide benefits including coastal protection and water purification. Yet habitat loss within the world's marine ecosystems includes a long list of destruction.

In the past two centuries, more than 85% of oyster reefs have been lost — making them one of the most imperiled coastal habitats on the planet.[19] For seagrasses, some areas are showing signs of stabilization and recovery after the removal of stressors such as coastal pollution, but a decline in the areal extent of seagrasses has occurred in many regions — current estimates put global seagrass loss at 19%.[20]

Mangrove areas are declining rapidly, with 16% of the 70 true mangrove species assessed as fitting IUCN Red List criteria for critically endangered, endangered or vulnerable.[21] Over the last 50 years, changes in the world's kelp forests indicate considerable geographic variation in the direction and rate of change.[22] On the whole, 38% of regions with existing kelp forests show signs of decline within those habitats.

These habitats — shellfish reefs, seagrasses and mangroves — represent important nursery areas and habitat for juvenile fishes, and their loss can place constraints on the productivity of fisheries.

Seagrass meadows provide nursery habitat to more than one-fifth of the world's largest 25 fisheries, and are vital to small-scale coastal fisheries because of their nearshore (shallow subtidal and intertidal) distribution. An estimated 4.1 million fishers are associated with mangrove fisheries globally, an affinity that becomes important for food security in coastal areas and countries that have large mangrove areas, such as Indonesia, Brazil and Bangladesh.

The effects of lost habitat can also be seen in the example of coral reefs. Recent estimates put the global loss of living reefs at approximately 50% from 1957 to 2007, with subsequent influences on fisheries and biodiversity; catch-per-unit-effort of coral reef associated fisheries has also decreased, by 60% since 1950 despite increased fishing effort,[23] and continued impacts from human activities indicate this decline could become as much as 70% to 90%, even if global warming is kept below 2°C.[24] Estuarine areas for anadromous fish, that spend part of their lives in fresh water and part in saltwater face continued pressures from development of hydropower.

RESOURCE EXPLOITATION

Unsustainable fishing practices can have major impacts on the marine environment, including loss of habitat as discussed above, reductions in biodiversity, unintended capture or bycatch of vulnerable species, ecosystem degradation, and altered food web dynamics, as well as loss of food and livelihoods for coastal communities.[25]

Abandoned or lost fishing gear from the 4.6 million fishing vessels across the world can negatively impact marine ecosystems and sensitive species and contribute to marine plastic pollution.[26] Currently, the FAO estimates that roughly one-third of fish stocks are fished at unsustainable levels and 60% of stocks are at maximum sustainable yield.[27]

CLIMATE CHANGE

Oceans have experienced acidification, coral bleaching, and extreme temperatures that have compromised productivity of wild fisheries. Seafood production is highly susceptible to climatic shocks, ecological and biophysical shifts in resources, and climate-related changes to species distributions or growth. Depending on the degree to which greenhouse gas emissions can be mitigated, decreases in the maximum catch potential in fisheries in the world's exclusive economic zones could be 2.8% to 5.3% by 2050.[28]

Mariculture will be affected by similar changes resulting in the need for ongoing adaptation. Seafood resources are some of the most highly traded commodities among food and agricultural sectors and the exposure of supply chains to climate-related disruptions can exacerbate vulnerability of mariculture to climate change.[29] Existing operations may need to be modified or moved in areas where sea surface temperatures become unsuitable for farming. There is also an increasing need to address threats from disease and antimicrobial resistance – risks that appear greatest in areas that are also the most vulnerable to climate change, such as the tropics and Asia.[30]

POLLUTION

Nutrient inputs to coastal environments are a major contributor to cumulative human impacts, and despite progress on addressing anthropogenic stressors to coastal areas, 59% of the ocean continues to experience cumulative impacts at an increasing rate.[25]

Many marine ecosystems now display the effects of that impaired function. Dead zones, caused primarily by eutrophication, continue to expand around the world. Because the vast majority of mariculture occurs in coastal areas, coastal water quality can also present a significant challenge to the health and productivity of this industry.

CONCLUSIONS

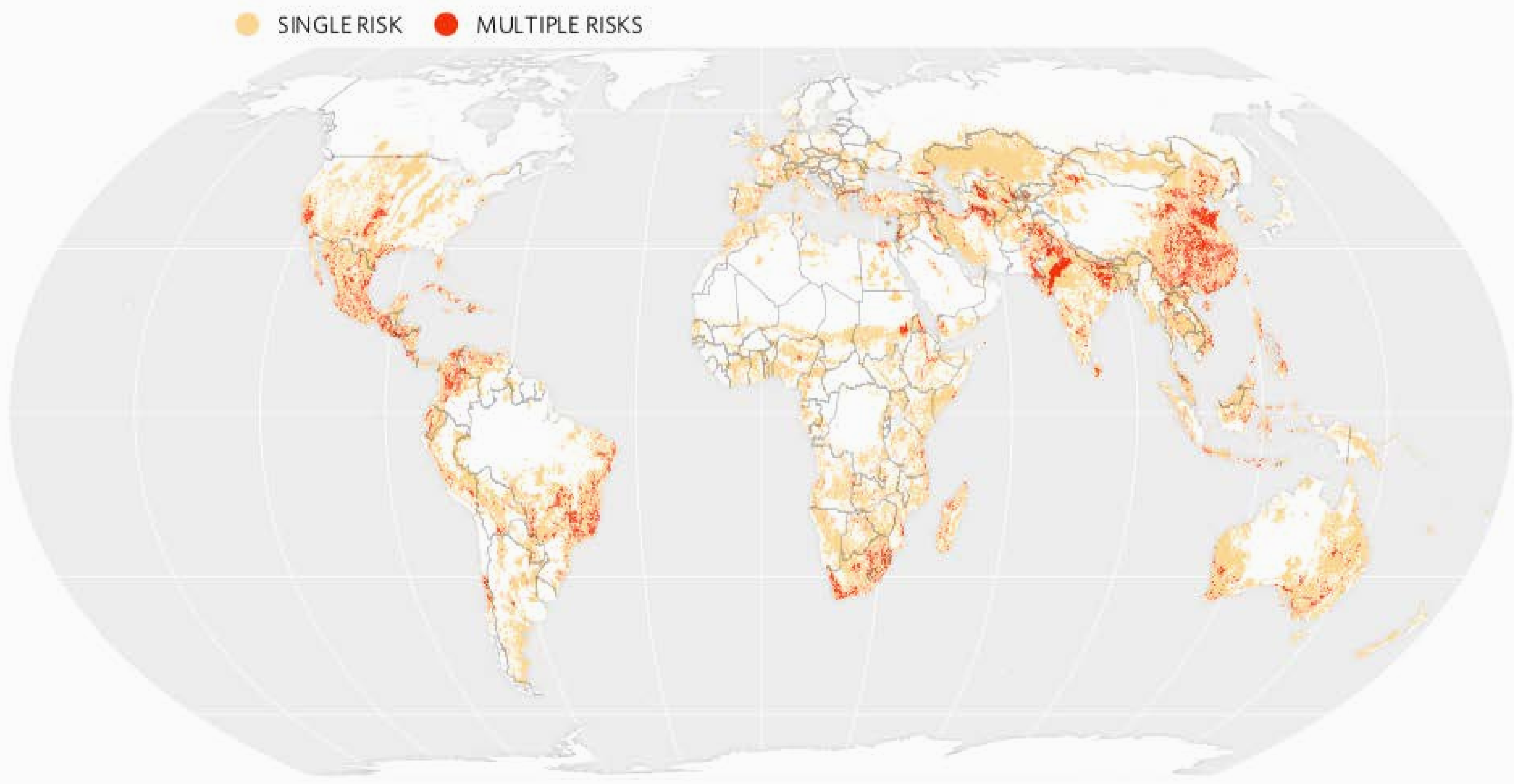
While Section 1 of the report highlights the extraordinary productivity of certain foodscapes, Section 2 demonstrates that even powerhouse foodscapes are not immune to the pressures of habitat loss, resource exploitation, climate change and pollution, all of which drive biodiversity loss.

Many foodscapes – especially intensively cultivated areas – are exposed to multiple interrelated pressures that in turn magnify and increase challenges across the entire global food production system (FIGURE 12). Foodscapes that are less intensive and/or in more marginal environments are also vulnerable to environmental pressures. Additionally, these less intensive production areas often support large populations of smallholders where threats to food production present acute risks to lives and livelihoods. These are the foodscapes that tend to be the major producers of food that humans directly consume, rather than producers of livestock feed and biofuels.

Ultimately all of these pressures go back to the central paradox of global food production: The world's food production systems – here presented in a spatially explicit global analysis and classification defined as "foodscapes" – depend on a healthy environment for their productivity. But, productivity in those same foodscapes is also a strong driver of environmental degradation.

While the multiple threats facing the world's foodscapes, as touched on in this section, appear dire, there is room for optimism. First, the sheer diversity – both of the world's foodscapes and the environments that underpin them – is an asset that can be the foundation of resilience in the face of change. Second, there are solutions at hand.

FIGURE 12: FOODSCAPE AREAS WITH MULTIPLE CONCERNS



Areas exposed to one or more of the following pressures: priority areas for threatened and endangered species, water depletion, climate risk, nitrogen surplus.

Among other approaches, nature-based solutions, especially, have the potential to restore degraded ecosystems and support diverse, productive, and resilient foodscapes.

But time is of the essence. Like similar analyses of the global food system, this work reinforces the urgency of the multitude of place-based transitions that are necessary for lasting transformation.

Right now, even as we begin to reckon with existing and anticipated changes, the scope and potential for nature to support healthy and productive foodscapes into an uncertain future remain underexplored.

Tea hills and flooded low-lying areas in
Phu Tho province, Vietnam
© Manh Cuong Vu/TNC Photo Contest 2021

SECTION 3

Foodscape Opportunities

Nature-based solutions have considerable potential to simultaneously mitigate the inter-related climate, biodiversity and water challenges facing the world's foodscapes while at the same time supporting improved livelihoods and well-being for food producers.

FOODSCAPE OPPORTUNITIES

Sections 1 and 2 of this report examined the world's current distribution of food production systems, as well as selected risks and pressures facing those systems and their productivity. Section 3 explores the opportunities to address challenges in foodscapes through nature-based interventions.

Iventions examined include agroecology, regenerative agriculture, restorative aquaculture, and restoration of the natural systems, such as rivers, forests, grasslands, estuaries and other habitats and processes, that ultimately underpin the world's foodscapes (see BOX 4, p.23)

Nature-based solutions can contribute meaningfully to more equitable and healthy food systems, in tandem with food waste reduction, shifts toward more sustainable diets, more inclusive governance, and targeted investment to meet the needs of the most vulnerable.[1,2] The ability to tailor these interventions within the context of a foodscape at a local level, from its cultures to its history, traditional practices, current governance and other circumstances, are essential to make the adoption of nature-based solutions and interventions more likely.

In this section, the analysis focuses on the potential for a series of specific nature-based solutions to mitigate the inter-related climate, biodiversity, and water challenges facing the world's foodscapes, as well as to foster nature-friendly food production methods on land and at sea:

- restoration
- agroforestry
- soil health management
- nutrient management
- water management
- restorative aquaculture

Each of the six nature-based solutions are first considered individually, and then at the end of the section the potential cumulative impact on two important outcomes, namely habitat and climate mitigation, are examined.

It is important to note that, by definition, restoration scenarios will require land to be taken out of production. Without question, the resulting loss of capacity for food production in specific ways in specific places must be accounted for and overcome. That said, the binary comparison of land in production and land in restoration ignores the many complexities and interactions between food systems and the environment.

Obviously, nature-based solutions to the world's food production challenges are not a panacea. They are, however, a vital – and often marginalized — part of that larger suite of policies, technologies and social levers around diet, resource management and economic opportunity that are necessary for any lasting, positive changes to the world's food production systems.

NATURE-BASED SOLUTION SCENARIOS

RESTORATION

Restoration, in the context of this report, is the revision of cropland and grazing lands back (as closely as possible) to their original habitats. Such place-based habitat restoration would emphasize reestablishment of an assemblage of species native to a given foodscape, including beneficial pest predators, pollinators and wild game. Restoration can also provide co-benefits such as carbon sequestration and mitigation of nutrient pollution and erosion. This analysis specifically focuses on quantifying the possible atmospheric carbon removal benefit of such habitat restoration.

That said, restoration of habitat is certainly not intended to exclude access of local peoples, and areas can continue to be managed for timber, wild honey and other products. Changing land uses from cropland and grazing to monoculture stands, such as coconut palm, eucalyptus plantations, and/or non-native species, can provide carbon benefits, but cannot be considered restoration per se, being unlikely to provide adequate habitat for a full range of native species, or to achieve broader goals of protecting and improving ecosystem services and biodiversity.

Cropland areas for restoration in this analysis were defined as those with (a) large or very large field sizes,[3] or (b) more than 70% of land in a given pixel in arable cultivation.[4] These areas were targeted because they are cultivated, highly fragmented landscapes where significant ecological benefit can be expected from reintroducing native habitat.

In each targeted pixel, 20% of cropland was "restored." This specific percentage was selected because it is the estimated minimum threshold of restoration necessary to provide significant benefits for both agriculture and biodiversity.[5] A more sophisticated assessment would include accounting for the extent of existing natural habitat, its fragmentation and the like.

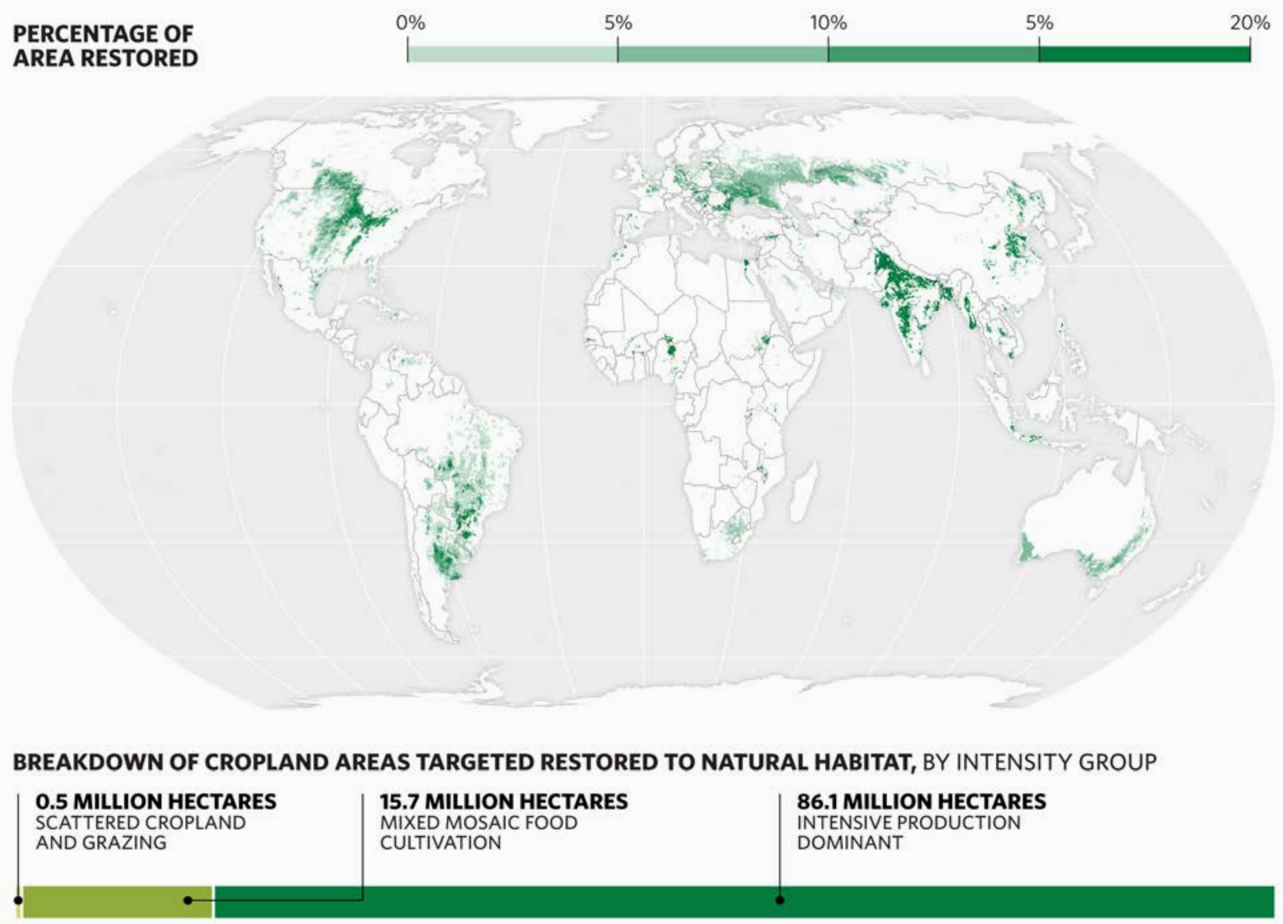
Such a restoration scenario leads to 103 million hectares of native habitat restored on former cropland, with 84% of the opportunity coming from intensive systems, such as maize and soy producing areas. It results in a global reduction of crop production of up to 10%, which will need to be compensated by higher yields on remaining cropland and in other foodscapes (FIGURE 13, TABLE 3, p.84).

As argued in Section 2, however, unless restoration at this scale occurs, productivity of these intensive systems will be compromised to the point that greater capacity reductions will still occur but in ways that, without a managed attempt at deliberate transition, are likely to be extremely chaotic. In terms of mitigation of climate change, IPCC parameters predict the level of cropland restoration proposed would lead to carbon removal benefit of 0.7 gigaton CO_2 yr^{-1} (TABLE 4, p.86).

In this scenario, restoration of cropland areas included the midwestern United States, northern and central India, southwestern Russia, and major cropping regions in southern Brazil and Argentina. In addition to these global priority areas, most foodscapes will have localized areas where restoration is important. Even in highly productive foodscapes, there are typically portions of farms that are less productive and profitable, and these can be restored at a lower opportunity cost.

Public policy and support programs, such as the Conservation Reserve Program in the United States, can help incentivize restoration of priority areas in croplands. The opportunity for habitat restoration in croplands is discussed further in the San Joaquin Valley foodscape Brief (p.161).

FIGURE 13. AREAS FOR HABITAT RESTORATION IN CROPLANDS



Global distribution of areas dominated by agriculture and/or large fields that would benefit from habitat restoration to increase ecological function and integrity. Size of bars indicates the areas of opportunity within the foodscape intensity groupings The color of bars indicates the intensity groupings: intensive production dominant (dark green); mixed mosaic food cultivation (light green); scattered cropland and grazing (yellow).

Grazing lands areas for restoration in this analysis are only those that were converted from native forest[6] to animal agriculture. In these areas, the scenarios explored the opportunity to sustainably intensify production on grazing lands via practices such as rotational, planned grazing and pasture improvement to release other areas for restoration. Restoring only previously forested areas that have been cleared for grazing back to native habitat allows for the most carbon benefit without inappropriately allocating trees to areas that were originally mostly or entirely grassland.

For comparison purposes, separate scenarios allowed ruminant stocking rates to increase to one of three levels:

- low: 1 livestock unit (LSU) per hectare
- medium: 2 livestock unit (LSU) per hectare
- high: 3 livestock unit (LSU) per hectare

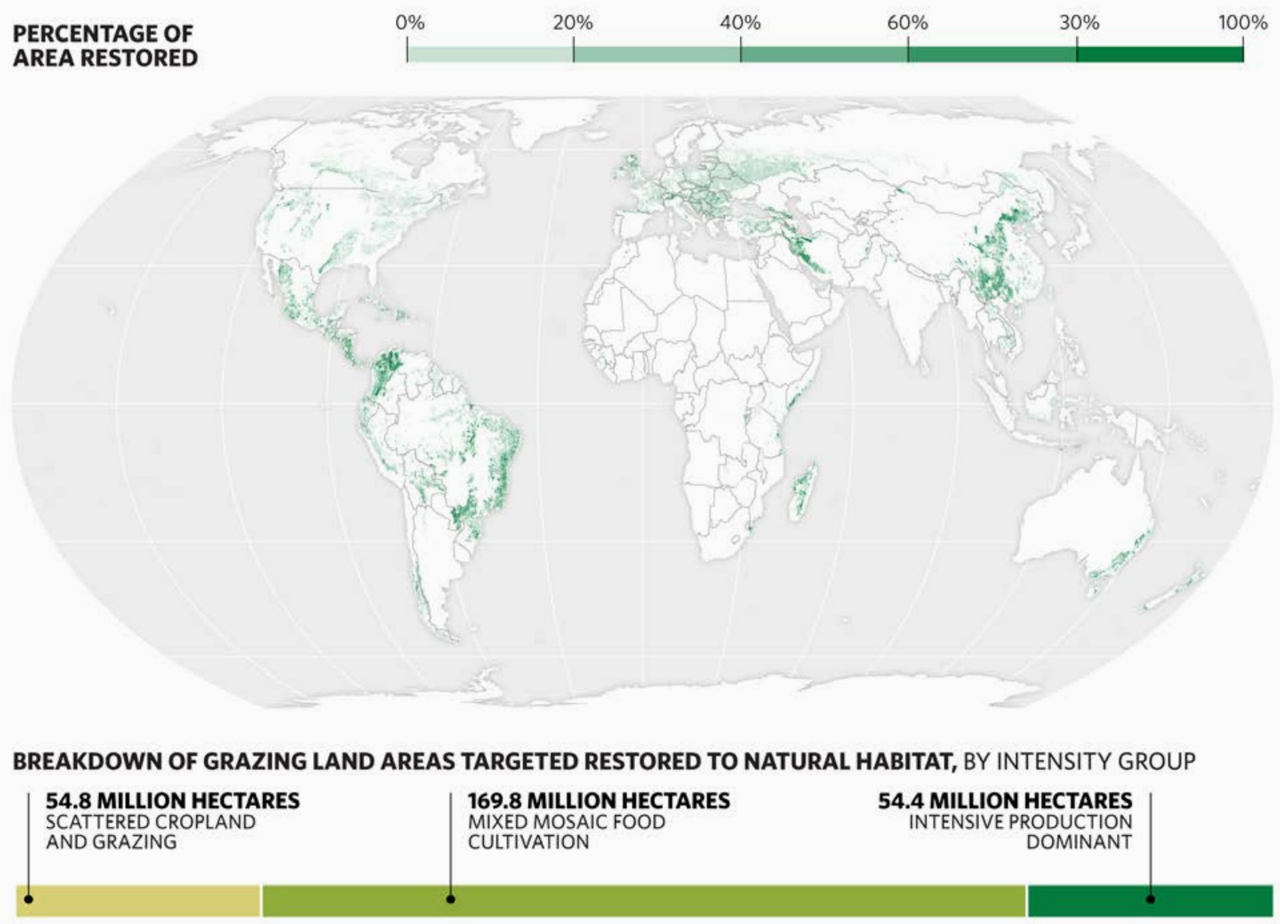
These improved management scenarios free up land for restoration of secondary forest on 195 (low), 283 (medium), or 325 (high) million hectares of land, respectively (TABLE 3, p.84). Based on IPCC parameters, this level of grazing land restoration is associated with potential carbon removal benefit of 1.5-2.6 gigaton CO_2 yr^{-1} depending on the scenario (TABLE 4, p.86).

Low productivity, scattered cropland and grazing areas account for 20% of the targeted restoration areas, with the rest coming from intensification in mixed (61%) and intensive (20%) systems (FIGURE 14).

Mediterranean forests were excluded from the analysis due to uncertain and variable productivity. Areas with significant opportunity for conversion of grazing lands back to native forest include the Atlantic Forest of Brazil, Central China and Iran, and the highlands of Colombia and Central America. Unlike cropland restoration, none of the modeled scenarios for grazing land restoration necessarily result in or require a concurrent loss of production.

The Growing Better Scenario of the Food and Land Use Coalition estimates a need for 1.2 billion hectares of crop and grazing land to be returned to native habitat, which is 3 to 4 times higher than the area identified by the analysis described in this report.[1] Achieving 1.2 billion hectares of restoration would require more aggressive innovations in the food system, such as large reductions in food waste, diet shifts, and a shift in protein supply to sustainable mariculture.

FIGURE 14. AREAS FOR FOREST RESTORATION IN GRAZING LANDS



Global distribution of grazing lands to reforest to increase ecological function and integrity. The mapped data represent the medium scenario. Size of bars indicates the areas of opportunity within the foodscape intensity groupings. The color of bars indicates the intensity groupings: intensive production dominant (dark green); mixed mosaic food cultivation (light green); scattered cropland and grazing (yellow).

AGROFORESTRY

Agroforestry is the integration of woody perennials into crop and grazing lands and includes many distinct practices. Importantly, agroforestry areas, by definition, continue to be used for crop and animal production as opposed to restoration scenarios as presented above. For this reason, crop and grazing lands are considered suitable for agroforestry interventions if ecological conditions allow.

In this analysis, the scenarios explore possible levels of agroforestry interventions that are most likely to maintain current productivity and ecological integrity. In agroforestry, in general, trees are arranged spatially (e.g., alley cropping, hedgerows, live fences), temporally (e.g., improved fallows) or more randomly distributed at different densities depending on agroecological context and management objectives.

In cropland agroforestry (here termed *silvoarable*), trees provide improved soil fertility (e.g., via nitrogen fixation), habitat for biodiversity, atmospheric carbon removal, income from timber and non-timber tree crops (e.g., fruit and nuts), and many more ecosystem services.[7] However, trees in croplands can also compete with crops for nutrients, water and light;[8] increase pest pressure;[9] and impede access for farm equipment.[10] This analysis focuses on quantifying the carbon removal benefit using published carbon coefficients.[11]

One scenario ("low") proposes a low tree density hedgerow system in which trees are planted 10 meters apart for cropland areas in both temperate and tropical zones. This low tree density scenario is intended to avoid possible competition between trees and crops for nutrients, water and light, and any increased pest pressure. Another more ambitious scenario ("high") follows the hedgerow tree density scenario above for temperate zones, but allows for more dense alley cropping in the tropics. In addition, because silvoarable interventions may be more difficult to implement in highly mechanized agriculture only half the density of trees is proposed in areas with large field sizes.

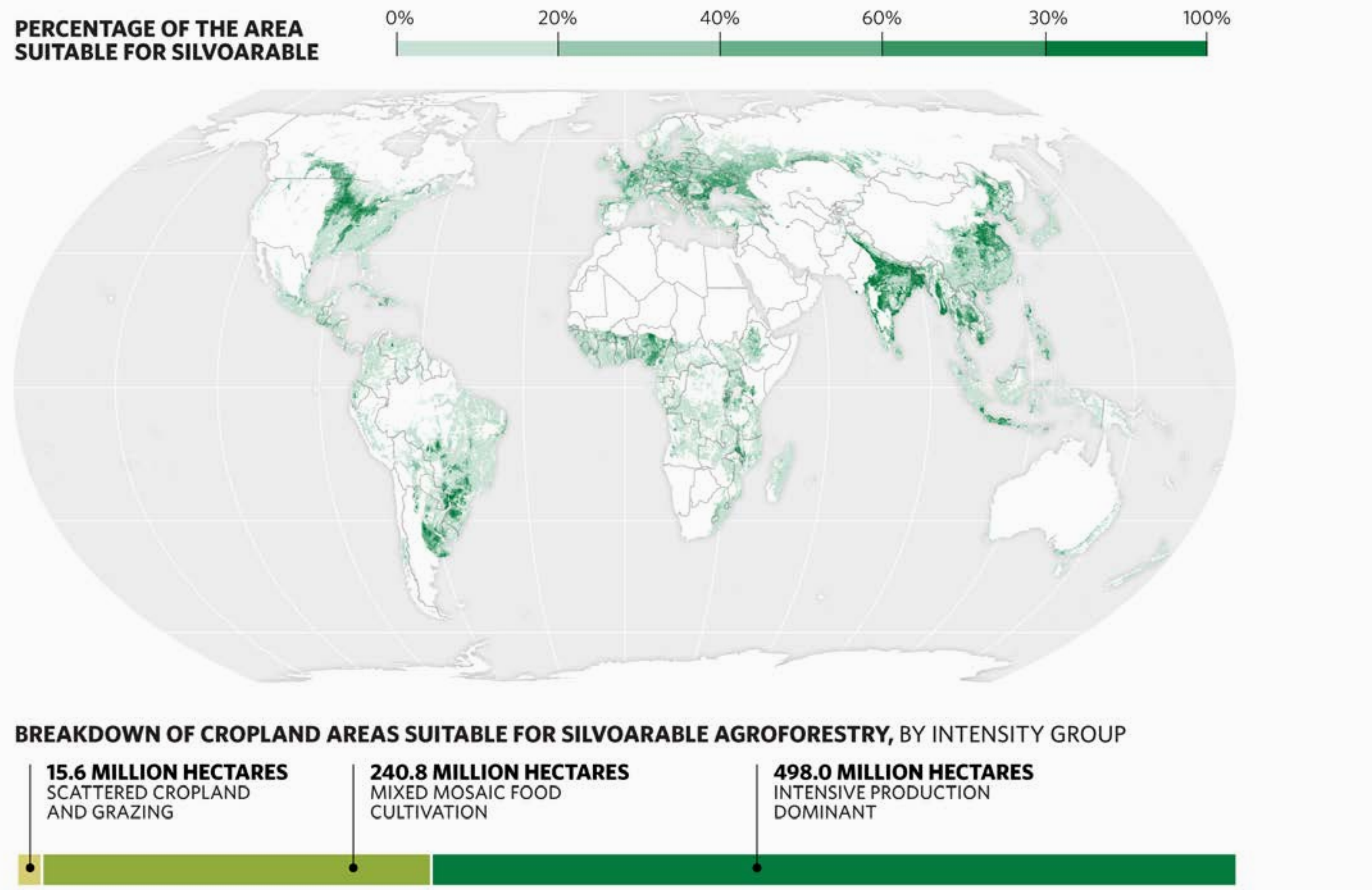
Overall, the analysis estimates 760 million hectares of croplands are suitable for silvoarable agroforestry (FIGURE 15, TABLE 3, p84), with an estimated carbon removal potential ranging from 3.1–5.9 gigaton CO_2 yr^{-1} based on IPCC parameters (TABLE 4, p.86).

Most of the opportunity for silvoarable agroforesty is in intensive production dominant or mixed mosaic system groupings of foodscapes (FIGURE 15). Opportunities for silvoarable systems are widespread, occurring in the North American Great Plains, across western Europe and Eastern China, throughout India, and in the humid tropics, including West and Central Africa, and much of the southern half of South America. See the Upper Tana River Basin foodscape Brief (p.169) for a more detailed discussion of the opportunity for agroforestry to support improved livelihoods and ecological outcomes.

While silvoarable agroforestry will almost always have strong carbon benefits, the manner in which it occurs is crucial in determining whether these practices provide habitat that has value for biodiversity. Under some typologies, monoculture stands of non-native fruit trees or eucalyptus wind breaks are considered agroforestry. Yet these systems may be of very low habitat value for native wildlife and may provide ecosystem disservices such as competition for water.

As described in the Upper Tana River Basin Foodcase Brief, farmers will often use the non-native *Lantana camara* as a hedgerow plant, which provides some habitat value for the endemic and endangered bird Hinde's babbler. Nevertheless, the ecological value of this hedgerow species is not as great as the native species that have been largely removed for agriculture.

FIGURE 15: AREA OF OPPORTUNITY FOR SILVOARABLE AGROFORESTRY



Global distribution of areas identified as having potential for silvoarable agroforestry, with different tree densities depending on local context. Size of bars indicates the areas of opportunity within the foodscape intensity groupings. The color of bars indicates the intensity groupings: intensive production dominant (dark green); mixed mosaic food cultivation (light green); scattered cropland and grazing (yellow).

In grazing lands agroforestry (here termed *silvopasture*), trees can be used not only to provide fodder and shade for livestock and serve as living fences, but also to improve habitat and support biodiversity. The benefits of silvopasture agroforestry are highly dependent on the native ecological context of the foodscape where they're being considered.

Silvopasture interventions in regions that were naturally open grassland (grassland ecoregions) can often cause or contribute to the problems, including water scarcity or erosion, they were originally intended to help solve, and trees can also compete with forage species for light and other resources. Thus, in this analysis grassland ecoregions are only considered suitable for low densities of trees (if at all), and all arid zones are excluded.

This analysis examines three silvopasture agroforestry scenarios that differ in how natural forestland and natural grasslands are considered, and levels of tree density:

- Low scenario: only areas in forest ecoregions, that is, where the natural vegetation is forest, are considered suitable for silvopasture[6] and these areas are only considered to support "parkland" systems, which are defined by a relatively low density of trees. Grassland ecoregions, that is, natural grasslands, are not considered suitable for intervention in the low scenario.
- Medium scenario: Grazing and pasture areas in both forest and grassland ecoregions are considered suitable for parkland systems, that is, for low densities of trees.
- High scenario: Grazing and pasture areas in forest ecoregions are considered suitable for high tree densities, while grassland ecoregions are deemed suitable for parkland systems.

The low scenario estimates 492 million hectares of potential silvopasture opportunity, and the medium and high scenarios identify 1267 million hectares (TABLE 3, p.84), with an estimated climate mitigation benefit of between 1.3 and 8.7 gigaton CO_2 yr^{-1} based on IPCC parameters (TABLE 4, p.86).

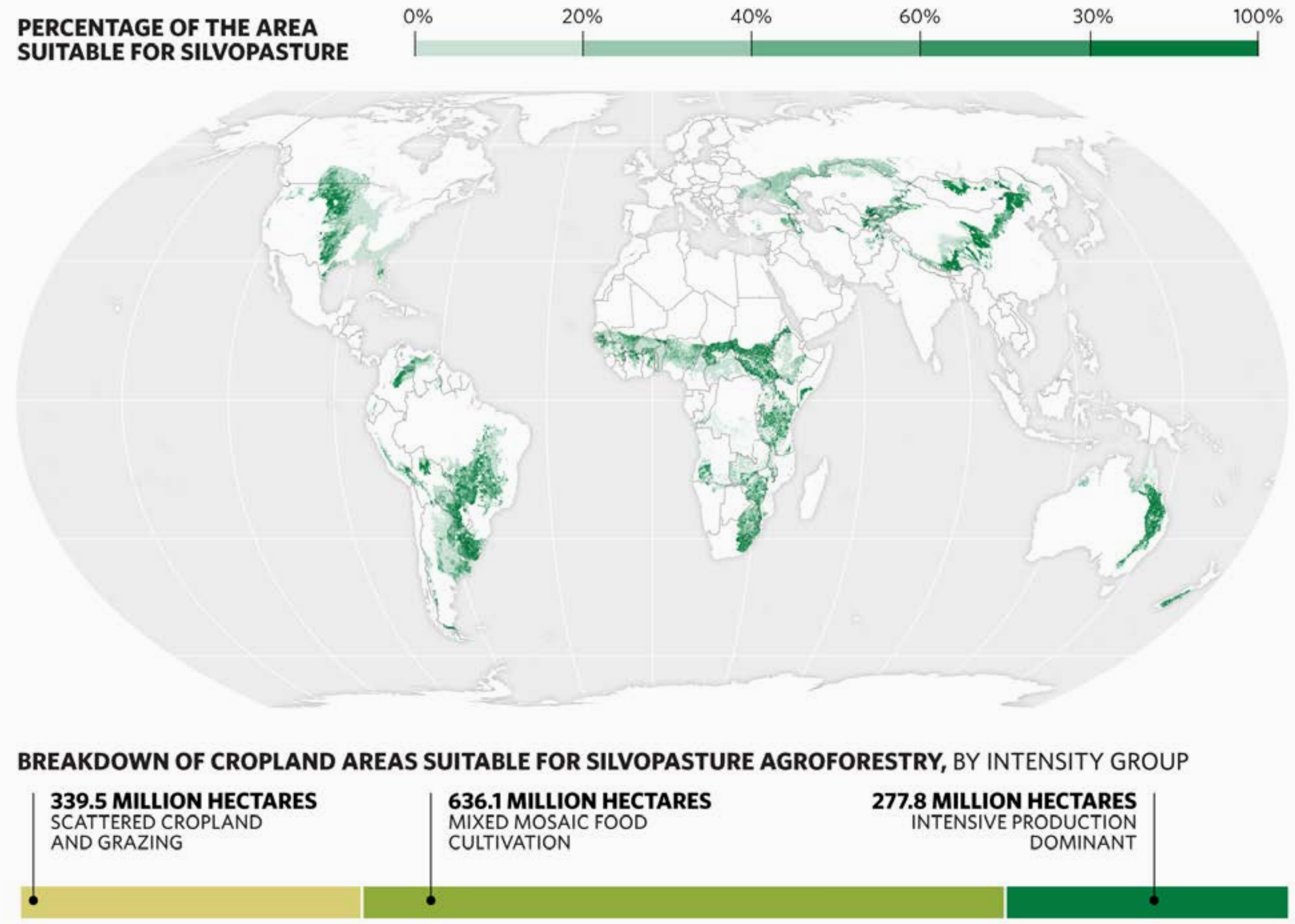
Half of this opportunity in the medium and high scenarios is found in the mixed mosaic foodscape grouping, with 22% in the intensive production dominant foodscape grouping and 27% in areas of scattered food production (FIGURE 16). Suitable areas occur in the central U.S., across the Sahel and throughout east and southern Africa, eastern Australia, central China, the Brazilian Cerrado, and Gran Chaco of Argentina, among other regions. Arid systems (aridity index < 0.2) are excluded.[12] See the Argentina Gran Chaco foodscape Brief for an example of silvopasture (p.103).

SOIL HEALTH MANAGEMENT

In its broadest and simplest meaning, the term soil health essentially describes the ability (or lack of ability) for a soil to support both agricultural production and other ecosystem services in row crop and grazing systems.[13] Soil health encompasses a broad range of elements including soil moisture and structure that moderate water cycling, soil biological activity that moderates nutrient cycling and carbon dynamics, and the like.

In this report, the analysis focuses on practices that build soil health and estimating the climate mitigation benefit of those practices through atmospheric carbon removal and storage in soils. The soil health building practices assessed here can often be used in combination with other interventions highlighted in this report, including nutrient management (e.g., fertilizer optimization and manure reuse), water management (e.g., irrigation efficiency), and agroforestry.

FIGURE 16. AREA OF OPPORTUNITY FOR SILVOPASTURE AGROFORESTRY



Global distribution of areas identified as having potential for silvopasture agroforestry. Mapped area represents the medium and high scenarios. Bars indicate the areas of opportunity within the foodscape intensity groupings. The color of bars indicates the intensity groupings: intensive production dominant (dark green); mixed mosaic food cultivation (light green); scattered cropland and grazing (yellow).

In croplands, soil health practices align with the main principles of conservation agriculture: maintain continuous soil cover through cover crops and mulching, minimize soil disturbance by reducing tillage, and rotate crops from year to year. The combination of such practices can improve soil structure and store carbon, which can in turn help reduce erosion, improve soil moisture, and provide other ecosystem services such as nutrient cycling.

In this analysis of croplands, the potential of cover crops and reduced tillage to store carbon in soils was assessed using two approaches. In the first approach, the "low" scenario, suitable area for cover cropping was based on SPAM cropland area limited to non-arid areas with low-cropping intensity,[4] and suitable area for minimum tillage was determined by two previous studies.[4,14] Suitable cropland area was thus determined to be 619 million hectares for cover crops and 845 million hectares for minimum tillage. Carbon build-up was determined using IPCC Tier 1 parameters. The low scenario resulted in a combined carbon benefit of cover crops and minimum tillage of 0.87 Gt CO_2 yr^{-1} (TABLE 4, p.86).

Horses drinking from a spring several hours east of Ulaanbaatar, Mongolia
© Iwan kristiana/TNC Photo Contest 2021

The second approach, the "high" scenario for cropland, used an estimate of cropland area available for intervention of 1,974 million hectares from European Space Agency land cover data, with carbon build-up based on implementation of an IPCC Tier 1 modeling approach such that potential soil carbon build-up rates varied dramatically across the globe driven by a combination of different response factors in different climate zones and different reference soil carbon stock values.[15] The high scenario estimates a carbon benefit of 2.68 gigaton CO_2 yr^{-1}. For more place-based discussion of soil health practices, see the Chesapeake Bay foodscape Brief (p.125) and the Punjab-Haryana foodscape Brief (p.155).

In grazing systems, soil health practices include pasture improvement, such as adaptive, rotational grazing, as well as the seeding of legumes and diverse forages. In the Arkhangai foodscape Brief, adaptive and rotational grazing are key management strategies for maintaining grassland productivity while also supporting biodiversity.

For grazing lands, the analysis considered the carbon removal and soil carbon storage potential of adaptive, rotational grazing management and pasture improvement. A potential area of 2,893 million hectares suitable for improved management was estimated using European Space Agency land cover data. Within that identified area, the IPCC Tier 1 modeling approach was then used to estimate the soil carbon sequestration impact of restoring degraded rangelands to either a nominally degraded condition (high scenario), or to the condition of an intensively grazed grassland (low scenario), together with at least one improvement to vegetative growth on intensively-managed pastures.[15] The two scenarios for grazing intensity on grazing land result in between 1.28 (low scenario) and 2.27 (high scenario) gigatons CO_2 yr^{-1} of carbon removal potential (TABLE 4, p.86).

NUTRIENT MANAGEMENT

Meeting a crop's nutrient needs is a central challenge of farming, and includes managing both micro- and macro-nutrients, as well as the conditions that govern their availability to plants (e.g., pH). Yet nutrient pollution — specifically nitrogen and phosphorus – can be a major driver of water pollution and, in the case of nitrogen, contribute to climate change.

While some foodscapes are facing severe overapplication of nutrients (see Section 2), others suffer from a dearth of nutrients, affecting plant nutrition and productivity. Closing nutrient loops and balancing nutrient inputs and removals is an urgent priority for meeting global goals not only for climate but also for food and water security.

There are many nutrient management strategies that can increase use efficiency and reduce losses to the environment. Focusing on nitrogen, this analysis has attempted to model the potential for four key interventions to reduce synthetic nitrogen fertilizer use, through efficiency gains and substitution with organic nitrogen sources:

- Reducing fertilizer application,
- Integrating nitrogen-fixing legumes into crop rotations,
- Optimizing the reuse of animal manure, and
- Diverting human manure from urban areas back to farmland.

These in-field practices can be complemented by other practices, such as the creation of vegetation buffers (a variant of habitat restoration), to further mitigate losses of nutrients to water bodies.

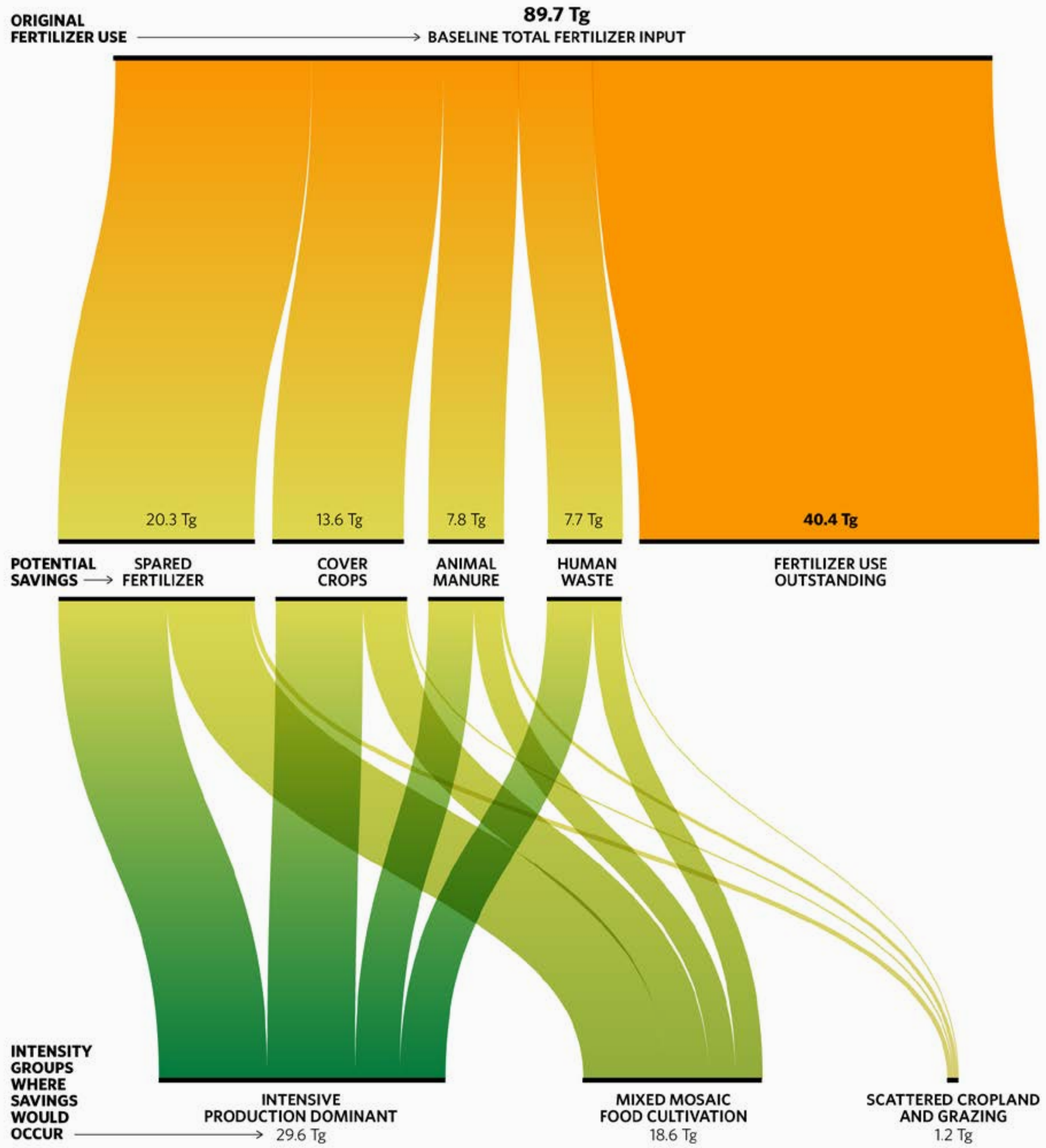
For areas with lower efficiencies (i.e., higher application rates with regard to crop removals), the excess application was treated as a potential savings achievable through better management. Second, the potential nitrogen that can be supplied by grass-legume cover crop mixes applied to croplands in line with the "soil health" scenarios above was estimated drawing on literature values for biological nitrogen fixation in cover crops. It was assumed that 30% of biologically fixed nitrogen would be transferred to subsequent crops. Third, the potential for improved recycling of manure to cropland was assessed. Additional elements for improved recycling of organic matter including compost, crop residues, and biofertilizers were not addressed here.

Current rates of nitrogen recycling from manure are approximately 20%,[16] due in part to much manure being deposited on pastures where it goes uncollected. Assuming that about half of the nitrogen deposited on grazing lands is necessary to replace nitrogen removed by grazing and browsing, there is still significant potential for recovery and reuse of additional manure.

Wherever additional manure was available within each 5 km by 5 km pixel, a nitrogen recovery rate was used to calculate the manure nitrogen available to replace synthetic nitrogen. The 95th percentile of present-day nitrogen recovery rates in each foodscape was applied, which typically involves recovery of 30% to 40% of manure nitrogen, with the remainder lost to the environment. This still represents an approximate doubling of contemporary nitrogen recovery.

Finally, the potential recovery and reuse of nutrients from human waste was estimated based on dietary estimates of nitrogen consumption, population density, and a 70% recovery ratio. The recovered nitrogen was then used to replace remaining synthetic fertilizer demand within a foodscape, in line with estimated availability and a "circular economy" approach.

FIGURE 17: POTENTIAL REDUCTIONS IN SYNTHETIC NITROGEN FERTILIZER USE



The top of the FIGURE indicates the current mass of synthetic nitrogen fertilizer applied to cropland annually (89.7 Tg per year). Below this line, the FIGURE shows the potential reductions in synthetic nitrogen that can be achieved through use efficiency, cover crops, manure recycling, and human waste recycling, and the potential for each of these strategies in urban, scattered, mixed mosaic, and intensive foodscape groups.

IIrrigation between seed beds,
Dome Valley, Arizona, USA
© Charlie Ott

The results of the analysis suggest there are significant opportunities to reduce synthetic fertilizer use in intensive systems in China and India to achieve higher nutrient use efficiencies (FIGURE 17). Grass-legume cover crop mixes offer widespread potential, in particular in the North China Plain, north-central Europe, and in the Sahel. In places with low nitrogen application rates, such as many parts of the Sahel, legumes can help address nutrient deficiencies.

Manure recovery and reuse opportunities are widespread, especially in mixed mosaic systems, although achievement of the potential modeled in this analysis will have considerable implications for the way in which livestock systems are managed.

Finally, opportunities for reuse and recycling of sewage are greatest in areas that combine high population densities with intensive agricultural production, such as eastern China and much of India. The scenario presented allows use of animal and human manure to substitute for nitrogen fertilizer only within the same 5 km by 5 km area, and thus does not rely on transport of materials over large areas.

The net effect of these interventions is a potential reduction in total synthetic nitrogen use of nearly 50 Tg (from 89.7 Tg to 40.4 Tg). This would be expected to deliver significant water quality and climate mitigation benefits. The technical potential of these solutions is even greater, with significantly more nitrogen available in manure and human waste streams than is applied annually as synthetic fertilizer. However, technical and transport cost barriers are an impediment to broader recycling.

WATER MANAGEMENT

Agricultural use of surface and groundwater accounts for about 70% to 90% of total global freshwater consumption,[17] making it the biggest anthropogenic driver of water depletion.[18] Opportunities for reducing the water footprint of foodscapes are many and include increasing irrigation efficiency, replacing crops with high water requirements, such as cotton and rice, with crops with lower water requirements such as sorghum or millets, crop management techniques such as direct seeding of rice and alternate wetting and drying, and investments in source water protection (e.g., water funds). In addition, the potential for rainwater harvesting (ex-situ and in-situ) in agriculture and its potential benefits for crop yields and water savings have been demonstrated empirically and in case studies around the world.

Here a simple scenario focusing on improved irrigation efficiency alone is presented. Global average irrigation efficiency is estimated to be around 20% to 30%[19] suggesting strong opportunity to increase water use efficiency interventions to enable reductions in surface and groundwater removals for irrigation. Such reductions can be accomplished through increasing water storage (e.g., rainwater harvesting), lowering evapotranspiration (e.g., mulching), or making water use more efficient (e.g., drip and precision irrigation technology). This cannot be overstated: effectively reducing water demand requires a simultaneous combination of improving water use efficiency and controlling water extraction.[17]

In the San Joaquin Valley foodscape Brief (p.161), state-wide water use restrictions will have a large impact on agriculture in the short-run, but when paired with nature-based interventions may lead to a more sustainable production system over the long run. In the Punjab-Haryana foodscape Brief (p.155), water use restrictions have created the unintended consequence of increased crop residue burning, which causes significant seasonal air quality problems in Delhi, India's capital city. Such a perverse outcome emphasizes the need to place efforts aimed at specific outcomes within the broader context of multiple ecosystem services and disservices from agriculture.

For this analysis, baseline irrigation was estimated with the LPJmL model,[19] crop water requirements were estimated using the Penman-Monteith method,[20] and the extent of irrigated areas was estimated using SPAMv2010.[4] To estimate the potential for improvement in irrigation efficiency, we first determined the water use efficiency of the top 10% of pixels in a given foodscape. This value was then assigned to the remaining 90% of pixels with lower water use efficiency. This implies a significant but achievable improvement over contemporary practice.

Achieving improvement in irrigation efficiency in line with that already achieved locally by best practice, that is, equivalent to the 90th percentile within a foodscape, would reduce global irrigation water withdrawals from 1,967 $km^3\ yr^{-1}$ to 1,664 $km^3\ yr^{-1}$, saving 15% of water removals. This scenario represents a shift toward best local practice in each foodscape. Seventy percent of this water savings comes from the intensive production dominant grouping, while 30% occurs in mixed mosaic food cultivation groupings, that have relatively smaller, but still important, areas of irrigated cropland.

There are notable limitations in such an analysis, one of the most important being that global irrigation datasets have many gaps, in particular for small-scale irrigation systems that are widespread throughout the world.

RESTORATIVE AQUACULTURE

It is estimated that edible food from the sea could be increased sustainably by 36% to 74% by 2050, through improved management both of wild fisheries and aquaculture.[21] Reform of wild fisheries management that addresses overexploitation and accounts for shifts in the distribution and productivity of species as a result of climate change, could yield higher catch and profits and potentially offset the negative impacts of climate change.[21,22]

Just as there are regenerative practices in agriculture, aquaculture also has a range of strategies that could simultaneously support food production and assist in the recovery of degraded aquatic environments (TABLE 2). For example, nutrient pollution can be managed by siting species such as bivalves in areas where nutrient mitigation is needed. In the Chesapeake Bay Watershed (see the Chesapeake Bay Foodscape Brief p.125) – research has demonstrated the ability of oyster reef restoration in tidal creeks and the wider bay to mitigate nutrient pollution. Regulators are considering allowing reef restoration, which can be supported by aquaculture, as an approved strategy to help meet nutrient reduction targets.

The analysis in this section focuses on the potential for regenerative aquaculture in marine coastal ecosystems.

Bivalves and seaweed are two species groups with the largest known potential for what is increasingly termed "restorative aquaculture". Currently, 48 million km^2 of currently unfarmed ocean space have been identified as biologically suitable for seaweed farming,[23] and a projected 30 times potential increase over current production is considered plausible for bivalve production.[21]

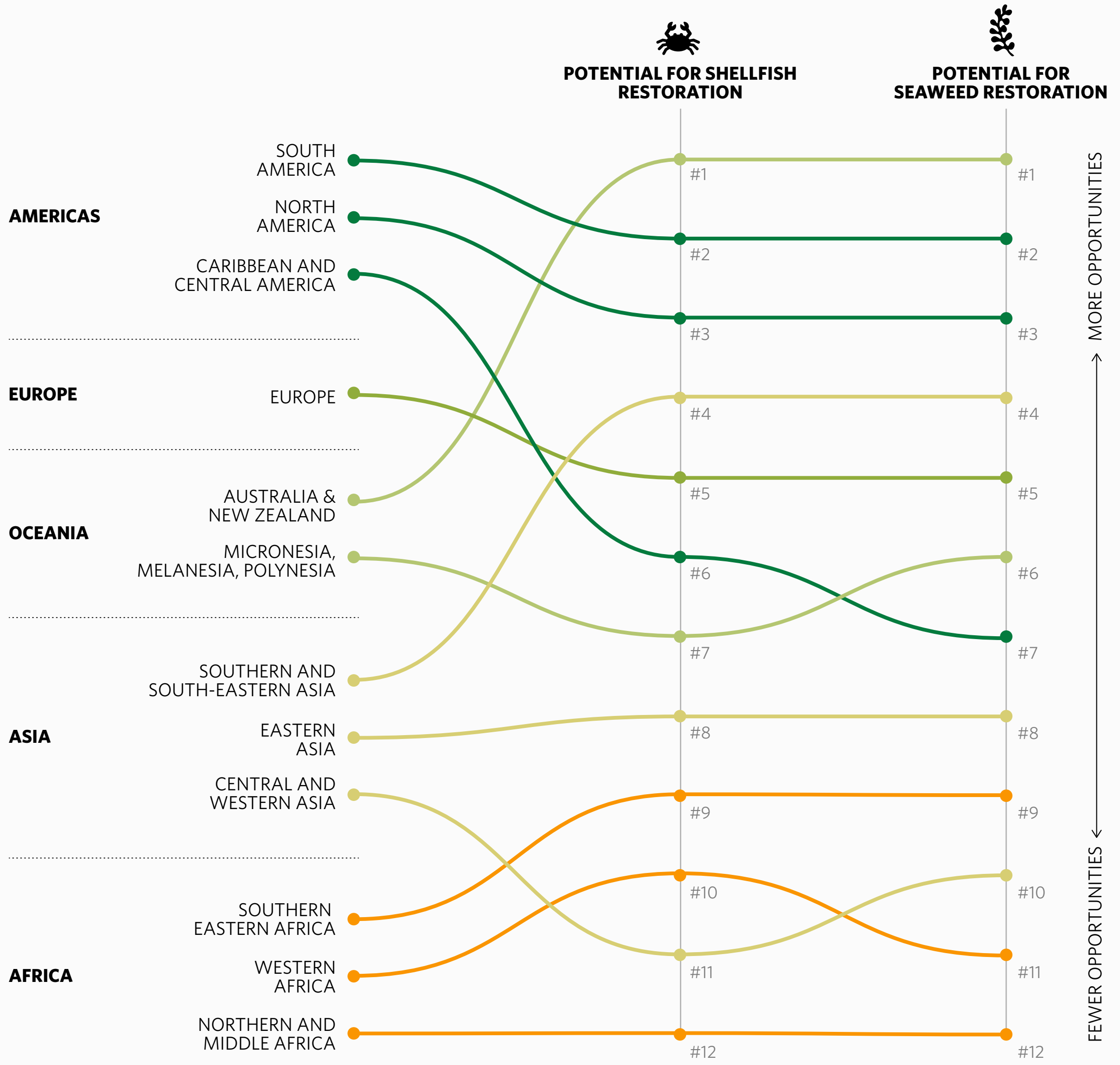
TABLE 2. EXAMPLES OF AQUACULTURE PRACTICES THAT COULD CONTRIBUTE TO A REGENERATIVE APPROACH IN AQUATIC FOODSCAPES

Examples of Aquaculture Practices
Cultivation of bivalves (such as oysters and mussels) or seaweed to increase water filtration and uptake of excess nutrients
Siting of aquaculture to avoid habitat impacts
Use of aquaculture to nurture species populations and stocks that have experienced declines
Use of selectively bred stock that can have reduced mortality (increasing yield from farming areas), or higher tolerance to sea surface temperature fluctuations or disease, and fallowing of finfish pens to reduce impacts of nutrients to benthic habitats
Use of farming strategies to maximize environmental benefits (e.g., timing the harvest of stock to preserve habitat benefits at the time of spawning for associated fish species)
Co-culture/polyculture; the addition of species to existing farms that can enhance natural functions (e.g., the addition of seaweed to reduce ocean acidification)

Seaweed and bivalves are non-fed, extractive species that improve water quality by removing nutrients (including nitrogen and phosphate) through water filtration, denitrification, and uptake in tissue and shell. The New Zealand Aquaculture foodscape Brief (p.117) demonstrates that production of seaweed could be integrated into existing mussel farms to create additional revenue, while also generating ecosystem services such as nutrient mitigation and carbon sequestration.

Mariculture has potential to support ecosystem services in many parts of the world. A recent study[24] considered 16 variables associated with environmental need, socioeconomic development, and human health factors in marine environment to establish a Restorative Aquaculture Opportunity Index and assess the potential of different countries (FIGURE 18). Encouragingly, the index indicates that at least one country in all regions of the world has the opportunity to gain substantially (very high opportunity) from restorative approaches in mariculture, with a majority of countries assessed as having an intermediate opportunity (medium and high). At a regional level, Australia and New Zealand, South America, North America and parts of Asia could benefit the most.

FIGURE 18: THE OPPORTUNITY FOR RESTORATIVE AQUACULTURE



Regional ranking of the potential for restorative shellfish and seaweed aquaculture. Rankings from Theuerkauf et al. (2019).[25]

Box 6 Food, nutrition and health

Nature-based transitions can help achieve global nutrition and health goals, in addition to the environmental and agronomic benefits highlighted in this report. Obesity — once primarily a problem of high-income countries — has now become widespread across all income groups, while undernutrition persists globally. This double burden of malnutrition[28] has prompted global dietary goals, such as the EAT-Lancet commission report,[29] that emphasize the importance of holistic diets and not just reductionist caloric targets.

The 'planetary health diet', which is intended to be locally interpreted and adapted, calls for more than doubling the consumption of fruits, vegetables, legumes and nuts, and globally a more than 50% reduction in added sugars and red meat globally. Overall, reversing global shifts toward simple cereals and diets rich in oils is a priority for food systems.[29] A shift from monoculture cereals to silvoarable agroforestry and diversified legume-cereal-pulse mixes all can support greater dietary diversification. Nature-based solutions are particularly well-suited to underpin and support transitions to diversification because they are often associated with change in a food production system as a whole, not just single practices.

In many cases, nature-based solutions create enabling conditions for multiple benefits from different actions, direct and indirect, across the global food production system. Practices that build soil organic matter, for instance, can increase crop yields,[30,31] nutrient densities of crops,[32] and resilience of crop yields to weather shocks.[33] However, whether increased crop nutrient density translates to improvements in human nutrition depends on food distribution and access, and physiological factors, such as prevalence of other forms of disease, which can amplify undernutrition. Such complex networks of connections, variables, feedbacks and dependencies mean that for us to realize the full suite of benefits nature-based solutions can offer to global nutrition and health goals, supply chains, public policies, and consumer demand must all shift so the scaling of these systems is viable and that necessary dietary shifts are accessible to all consumers.

Nature-based solutions can also be associated with varied impacts on crop yields. For example, the use of conservation agriculture — has been shown to lead to positive, neutral, and negative impacts on crop yields.[34] — Some practices or systems — such as perennial cereals[35] and organic agriculture[36] have also been associated with lower per hectare yields. Critics argue that this poses risks to environment and food security because it requires expansion of agricultural area. Proponents of these practices have argued that alternative systems can produce more food on aggregate even if yields for single commodities are lower, and will ultimately have higher yields over time because they are less degrading of the natural resource base.[36,37] Still others note that a shift away from using land for commodities that are not allocated directly to food is an opportunity to reduce expansion of agricultural area without compromising healthy food supply.[38]

NATURE-BASED SOLUTIONS SUMMARY HABITAT AND CLIMATE

HABITAT

Of the nature-based solutions described here, restoration and agroforestry can be understood to have a positive impact on habitat, through either restoration of secondary forest or restored natural grasslands, or the creation of areas with biodiversity-friendly farming.

The analysis finds that agroforestry in croplands and grazing lands can be applied in some form to the largest global land area, potentially improving habitat over a wide swath of the world's foodscapes, with relatively limited impacts on production. In total, the analyses estimate between 1,252 million hectares and 2,027 million hectares of agroforestry potential in both grazing lands and croplands, which accounts for between 13% and 21% of the world's total crop and grazing land area.

Straight habitat restoration is applied to a smaller land area, due in part to tradeoffs with production, yet offers more habitat benefit per hectare than agroforestry (TABLE 3). Careful targeting of restoration can maximize important ecological benefits while minimizing the opportunity cost for food production.

Importantly, this analysis does not consider interactions with potential gains in crop yield that could enable restoration while maintaining current patterns of food production. Nor does it evaluate more aggressive transformations of the food system, such as major shifts in crop distribution or food trade, large dietary shifts, and new innovations in reducing food waste. Collectively, these actions could enable significant additional opportunities for restoration. In aquatic ecosystems, restoration using seaweed and bivalves contributes both to environmental benefits and food production, and is therefore not subject to the same types of trade-off considerations as terrestrial food production.

TABLE 3. HABITAT SUPPORTIVE OPPORTUNITIES

Category	Scenario*	Area (Mha)
Cropland Restoration		103
Grassland Restoration	Low	195
	Medium	283
	High	325
Silvovarable Agroforestry	Low, High	760
Silvopasture Agroforestry	Low	492
	Medium, High	1267

*see text for full description of the scenarios

Areas of improved habitat either through restoration of natural habitat types or biodiversity friendly farming, associated with restoration and agroforestry as evaluated in this report. For silvoarable agroforestry in croplands, both scenarios have the same area. For silvopasture, the medium and high scenarios have the same areas. The differences between the scenarios refers to tree density. Note that area targeted is unconstrained by local feasibility or current adoption rates.

A man casting a fishing net into a river in West Bengal, India
© Chinmoy Biswas/TNC Photo Contest 2021

CLIMATE

Because food production is responsible for up to 35% of global GHG emissions, there is significant interest in whether nature-based solutions can contribute to climate mitigation. Of the nature-based solutions assessed here, scenarios for restoration, agroforestry and soil health management were evaluated for their climate mitigation potential through atmospheric carbon removal and storage in vegetation and soils.

Because it was focused on carbon removals, this analysis does not present a complete picture of the mitigation potential associated with nature-based solutions in food production. Such solutions can also reduce emissions of CO_2, N_2O, and CH_4, either directly, through changes in use of farm equipment that burns fossil fuels, or indirectly, through changes in management practices that lower rates of emissions of N_2O and CH_4 from soils and livestock. Changes to animal agriculture are especially important: 57% of all food production emissions are from animal agriculture, and recent research on short-lived pollutants like CH_4[26] highlights that rapid emission reductions could have outsized impact on climate mitigation goals.[27]

The potential for carbon storage is greatest from agroforestry in croplands and grazing lands because of the large area of opportunity and high rates of sequestration. Global carbon sequestration for agroforestry scenarios ranged from 3.1–5.9 gigaton CO_2 yr^{-1} for silvoarable agroforestry and 1.3–8.7 Gt CO_2 yr^{-1} for silvopasture agroforestry (TABLE 4).

This analysis presents global technical maxima because it does not take into account where practices are already adopted, due in part to limited data availability. The potential for carbon removals has generated strong debate around the appropriate area of opportunity, the risks of impermanence, and other concerns that are not addressed here.

TABLE 4. CARBON STORAGE OPPORTUNITIES

Intervention	Scenario*	Gt $C0_2$ yr^{-1}**
Cropland Restoration		0.66
Grassland Restoration	Low	1.54
	Medium	2.28
	High	2.62
Cropland Soil Health	Low	0.87
	High	2.68
Grazing Land Soil Health	Medium	1.28
	High	2.27
Silvorable Agroforestry	Low	3.14
	High	5.87
Silvopasture Agroforestry	Low	1.31
	Medium	3.42
	High	8.68

*see text for full description of the scenarios
**annual accrual for a 20 year period

Total technical potential of carbon storage associated with different nature-based solutions evaluated in this report. Carbon storage rates are determined by assessments of areas of opportunity and IPCC Tier 1 approaches. Each intervention should be assessed independently because combining interventions would lead to double counting in land area.

Shepherds bringing livestock back from high pastures, Ladakh, Kashmir
© Olivier Boels/TNC Photo Contest 2021

Farmers working in paddy fields,
Sauraha, Nepal

CONCLUSION

Section 1 of the report highlights the diversity of global foodscapes, and Section 2 demonstrates the multiple pressures facing today's foodscapes, including habitat loss, resource exploitation, climate change and pollution. Section 3 explores the opportunity for nature-based solutions in food systems to simultaneously mitigate the inter-related climate, biodiversity and water challenges facing the world's foodscapes while at the same time supporting improved livelihoods and well-being for food producers.

These nature-based solutions include cropland and grazing land soil management, nutrient management, water management, agroforestry and habitat restoration. Fundamental to this approach is recognition that changes in in-field practices, incorporating natural elements into agricultural landscapes, and full restoration of some existing agricultural areas are all essential to achieving agricultural and environmental goals.

The global potential benefits of nature-based solutions are estimated through a series of spatial analyses and modeling that point in the direction of specific foodscapes and foodscape groups in regions and countries where actions will make the greatest contribution to global goals. Intensive production dominant foodscapes offer the greatest opportunity for nitrogen fertilizer reductions, water savings, silvoarable agroforestry and cropland restoration. Mixed mosaic foodscapes offer the greatest opportunities for silvopasture agroforestry and grassland restoration, and also have significant opportunity for reducing synthetic nitrogen fertilizer use and saving irrigation water.

While the transitions modeled here are constrained by distribution and composition of today's foodscapes, this is not a modest agenda for action. It identifies enormous areas of opportunity for improving habitat, storing carbon, reducing synthetic nitrogen use, and reducing water use for irrigation.

Estimating potential benefits at the scale of specific regional foodscapes is an important next step needed to build a shared vision of how to move toward transition in specific foodscapes.

More work is needed to understand and spatially quantify potential outcomes from foodscape transition and transformation. The need is urgent for further work to enable better modeling of potential changes in net greenhouse gas emissions from foodscapes, to compliment the work on carbon removals. Also important is the need to address pesticide use in food production, given their strong negative impacts on non-targeted species including people.

Other priorities include building in feedbacks from food system changes and spatial prioritization and impact assessments for restorative aquaculture. For aquaculture in particular, research on the environmental benefits of nature-based solutions is growing, but requires greater attention to analyzing trade-offs and determining how operations and practices can be best designed to deliver benefits.

A field of spring onion vegetables farmed to be sold at market in the village of Doura, Mali
© John Images/Getty Images

CONCLUSIONS

Toward a Nature-Based Transition

Complex trade networks crisscross the globe, connecting hinterlands and oceans with urban and industrial centers in a system that feeds the planet. Yet despite the global nature of the food system, food production remains a profoundly local process, rooted in a particular place and ecological context. This report proposes a new concept—the foodscape—to try to capture the distinct combination of biophysical and management factors that shape and make up the places where food production happens.

TOWARD A NATURE-BASED TRANSITION

Foodscapes are diverse, ranging from intensively cultivated “breadbaskets” to sparsely populated rangeland, with a remarkable amount of the world’s food coming from a relatively small set of foodscapes. The foodscape concept is intended to widen the focus from a narrow commodity/yield perspective to one that captures and actively encourages a diversity of production systems—multi-crop rotations, integrated crop-livestock systems, restorative aquaculture, etc.—within their proper ecological and landscape context. While each foodscape is distinct, they are all embedded within the global food system and are subject to the influence of demand signals, policy shifts, and socio-cultural change, among other factors.

The world’s foodscapes face an array of challenges, including climate change, resource exploitation, pollution, and the loss and degradation of native habitat and biodiversity. This report highlights the ways in which foodscapes both contribute to and are affected by these interrelated pressures. Most of these pressures transcend the boundaries of any given foodscape: greenhouse gas emissions anywhere drive climate change everywhere. Nutrient runoff from farm fields in a deep interior can cause algal blooms and dead zones that impact coastal fisheries and ecosystems on the edge of a continent, stitching together land, fresh water and ocean in a shared and largely avoidable cost of food production.

Some of the world’s most intensively cultivated foodscapes are exposed to multiple pressures, calling into question the long-term resiliency of production. Simultaneously, hotspots for risk also include areas that appear marginal in terms of overall production but are critical for supporting livelihoods and local access to a food base, emphasizing the limitations of an approach that measures food systems only in terms of productivity rather than how diversity of production underpins rural livelihoods and spreads risk, particularly relevant as climate change bites and the resilience of food production becomes a priority.

A shepherd returning home in the evening after heavy rain, Bangladesh
© Mukul Ahmed/TNC Photo Contest 2021

In identifying foodscapes, researchers sought to understand how these distinct patterns affect the suitability and potential of a suite of nature-based solutions. The foodscape concept was designed so that each foodscape class can serve as a distinct planning unit, with potential transitions applying across a foodscape, regardless of jurisdiction or other boundaries. In this vein, the analysis modelled the impact of some of these solutions at the global level. Recognizing the importance of sociopolitical and cultural context, the analysis has gone more deeply into individual foodscapes (FOODSCAPES IN FOCUS p.95) to explore the impact of specific transitions. The nature-based solutions are well known and have been well documented, in this report and elsewhere:

- Restoring degraded habitat
- Diversifying production systems
- Rebuilding soils
- Reducing chemical use and pollution
- Extending agroforestry
- Incorporating native habitat into agricultural production areas
- Replacing pesticides with integrated pest management systems
- Restorative aquaculture
- Improved management of wild fisheries
- Halting loss of forest, wetlands and natural grasslands

This research demonstrates the potential for nature-based solutions to contribute to climate goals, but this is much more than a climate strategy. In the same way as the challenges foodscapes face have several mutually reinforcing sources, nature can deliver multiple, overlapping solutions—for climate, but also for food production, biodiversity, freshwater, oceans and the lives and livelihoods that depend on them.

The reality is, however, that despite widespread latent potential in the world's foodscapes, the adoption of nature-based solutions remains low and highly variable, reflecting the challenges of achieving even modest transformation in the global food system. Foodscapes are the products of their history, and the parameters set by history, in food production as everywhere else, can be hard to transcend. Policy, regulatory and subsidy frameworks, market incentives and demand signals, transport and infrastructure, education and extension services—many of the elements that shape the global food system we have today evolved at a time when awareness of accelerating climate change and biodiversity loss was much lower than it is today.

Today, there is much greater willingness to take on the challenge of food system transition, as business as usual is no longer an option. The world's foodscapes, the building blocks of the entire global food system, face acute pressures, and action is needed now. Fortunately, there are many no-regrets opportunities to help foodscapes transition to nature-based solutions for food production at a scale and pace that matches the urgency of the needs.

First, there is an urgent need for public sector regulatory reform and investment at a scale equal to the urgency of the challenge. Public policies are still being shaped by historical development imperatives that have led to subsidies that focus primarily on maximizing yield. It can be argued that one of the biggest subsidies is ignoring environmental and social externalities either by lack of regulation or poor implementation of existing regulations. At the same time, many of the public benefits (or goods) that are generated in the world's foodscapes – carbon storage, clean air and water, habitat and biodiversity – remain external to markets. In this sense, producers do not reap what they sow.

The actions of governments can be one of the most powerful drivers of food systems transition. There is an increasing awareness among policy makers that food systems need to address environmental and nutritional outcomes while also ensuring food security and livelihoods for farmers. Governments have options for changing the economics that drive actors in the global food system. They can realign incentives through public policy and regulatory frameworks, including by repurposing subsidies towards supporting nature-based solutions and creating mechanisms to reward producers for public benefits. Reforming subsidy and regulatory frameworks is hard, but such reform is critical to the transitions necessary for lasing transformation of the global food system.

New public investment will be needed to achieve the large-scale transitions envisioned in this report. Conserving biodiversity and restoring habitat – one of the critical nature-based solutions needed for healthy and productive foodscapes – requires investment. The recent report, Financing Nature: Closing the Global Biodiversity Funding Gap, estimated a funding gap of $598 billion to $824 billion per year between currently available public financing levels and the investment required to guarantee the biodiversity and habitat protection that are central enabling factors in a range of nature-based solutions.

Second, the private sector must actively support a transition toward nature-based solutions. Supply chains run within and between foodscapes, and there is no greater and faster scaling mechanism than markets. Industry can play an important role in setting the direction of change by establishing nature-friendly standards around land conversion, soil health, water use and management practices in general, and actively helping producers to meet them in a way that is supportive of rural livelihoods.

Private sector action will need to be ambitious, investing in foodscapes, as well as the jurisdictions and supply chains within them, at a large scale and accelerated pace. Investments should be stress-tested against sustainability benchmarks such as net-zero commitments and science-based targets. To drive transitions will require new business models, creative collaborations and market transparency. Bold commitments and new approaches need to be followed by corresponding investment. This includes partnerships to secure the financing that producers will need to make the transition to nature-based solutions, which will require much more active involvement of financial institutions and the finance sector in general. Many companies are realizing that long-term profitability, as opposed to short-term gain, depends on the continued health and productivity of the ecosystem services on which their supply chains depend.

The adoption of nature-based solutions will not be without friction. There will be conflicting perspectives regarding the priority, pace, and scale of implementation, both with regard to alternative solutions and approaches. Interventions in foodscapes will have both intended and unintended consequences. Adoption, scaling and behavior change are influenced by culture and deeply-rooted preferences. This demands a strong role and voice for civil society in engaging collaboratively around food system transformation, including nature-based solutions. This is especially important to ensuring that food system transitions unfold in ways that are just and equitable, rather than perpetuating the deep inequities and injustices in today's food system.

Action and engagement on food system transformation requires transdisciplinary science and research. Some of the existing research gaps have been identified in this report, particularly the need to bring data and findings around aquatic and marine production systems up to the level of terrestrial systems. The solutions themselves are inter-dependent requiring simultaneous shifts in different sectors and components of the food system. Both the public and the private sector have their roles to play in fostering the science and applied research needed to underpin food system transition.

Finally, and arguably most importantly, we need the full engagement of food producers, and the communities in which they live. Food system transition, nature-based solutions, climate resilience, productivity and output, biodiversity enhancement -- all ultimately depend on decisions made, or not made, by food producers on land, and in rivers, lakes and oceans. The communities in which they live can be affluent or poor, their food production systems diverse or uniform. They all need, from their different starting points, to envisage a better future, to develop more fully what food system transition involves for them, their families, their livelihoods and their communities.

One thing food producers most need right now is space: space to be listened to, space to engage in conversations, and space to obtain the resources they need. They also need space for experimentation and knowledge building in foodscapes such that same or similar foodscapes can learn from each other's experiments and experiences, and communities of practice can emerge within geographically distributed but similar foodscapes.
In that space, given the pragmatism that characterizes farmers, fishers and pastoralists at local levels pretty much everywhere, what might emerge is a more pragmatic food system, one that synthesizes the productivity gains of the industrial agricultural systems with the more diverse and environmentally more sophisticated approaches of other more historically established forms of agriculture. The concept of a foodscape is designed to help that process.

Farmer picking tea leaves
in the Upper Tana River Basin, Kenya
© Nick Hall

Foodscapes in Focus

Foodscapes and Nature-Based Solutions in the Real World

FOODSCAPES IN FOCUS

To shed light on the role of nature-based solutions in different contexts and understand local transition processes, this section presents a series of terrestrial and aquatic foodscapes across all continents. While by no means exhaustive of all food production systems, these brief foodscape stories illustrate the diversity of relevant nature-based solutions that might apply, the multiple means for scaling adoption, and the different sources of value such solutions can unlock for producers and the public.

The foodscape classification featured in this report represents biophysical and management factors that shape foodscapes' suitability for nature-based solutions. Yet this only tells part of the story. The specific pathways to adoption of such practices depend on the political, cultural, economic, and historical backdrop against which any change would take place.

Unfortunately, there are no global data for mapping these factors, so this report presents a group of foodscapes to shed light on the role of nature-based solutions in different contexts. These foodscapes illustrate different types of solutions, multiple means for scaling adoption, and different benefits provided to food producers and the public.

The nature-based solutions examined here include methods of agriculture, aquaculture, mariculture, and fisheries that support food production, livelihoods, climate mitigation, resilience, and biodiversity. There is a great deal of variability in the relevance of different approaches in different foodscapes, as well as the magnitude of benefits derived from these different nature-based solutions. To get a clearer understanding of those variables, this report includes an economic analysis of the costs and benefits of transitioning to nature-based solutions for a subset of the foodscapes. Seeing the foodscapes as a set of distinct but related systems provides new insights into what is needed to achieve the place-based transitions necessary to realize transformation of the global food production system.

Fram hand/Gardener of life
© Heinn Htet Kyaw

FOODSCAPES AFFECT AND ARE AFFECTED BY LOCAL LANDS AND WATERS

Land and water systems influence and affect each other: excess nutrients from agriculture can cause biodiversity declines in marine systems. These links highlight the need for policies and approaches that marry the management of foodscapes with management of connected lands and waters. In the Chesapeake Bay Watershed foodscape (United States), a growing body of evidence shows that oyster bed restoration is effective at remediating excess nitrogen. Regulatory frameworks for nutrient loading in the Chesapeake Bay Watershed foodscape may soon allow for oyster bed restoration to be included as an allowed activity toward meeting nutrient reduction targets. In the Upper Tana River Basin foodscape (Kenya), there is a growing effort to couple water sediment reduction targets with crop production targets by promoting the use of rainwater collection systems that both reduce erosion and provide water for irrigation. In the Mopti foodscape (Mali), management of seasonal flood waters of the Niger River ensure fish for local fishers, elephant grass for livestock herders, irrigation water for rice farmers, and habitat for one of the most biodiversity-rich areas of the Sahel.

GOVERNANCE MECHANISMS ARE A NECESSARY PRECURSOR FOR NATURE-BASED SOLUTIONS

Most foodscapes include multiple types of land use, and ensuring governance mechanisms to manage those land uses is often a necessary precursor for implementing nature-based solutions. In the Mopti foodscape, traditional methods of adjudicating land use tensions among farmers and herders have been complicated by an escalation of armed conflict in the region. Implementing effective nature-based solutions requires adequate land tenure policies to allow farmers to invest in practices such as agroforestry while also requiring flexible governance mechanisms that allow semi-pastoral herders to access adequate forage throughout the area. In the Arkhangai foodscape (Mongolia), lack of private land tenure has limited the ability of herders to invest in practices that maintain land quality. Creating community-based conservancies that have some degree of land use rights is a necessary precursor for promoting grazing practices that restore forage production and biodiversity habitat.

POLICIES ARE NECESSARY FOR CHANGE BUT ARE OFTEN INSUFFICIENT AND CAN HAVE UNINTENDED CONSEQUENCES

Evidence-based policies are necessary for achieving environmental and food production targets. In the Chesapeake Bay Watershed foodscape, 30 years of investment in science has created actionable targets for nutrient reduction. This has enabled adaptive management of the foodscape as progress toward those targets is evaluated. To be effective and sufficient for change, policy solutions must be rooted in evidence, come with vehicles for compliance and enforcement, and must not be focused narrowly on single problems. There are rarely, if ever, single interventions that solve problems over the long term; singularly focused policies often create serious unintended consequences.

In the Argentina Gran Chaco foodscape, a Native Forests Law has established zones where land conversion is illegal, yet illegal land conversion is still widespread. In the Punjab-Haryana foodscape (India), government provision of free electricity to rural areas drove high rates of groundwater pumping and overdraft. Policies then

A fruit vendor weighs fruit in East Kalimantan, Indonesia.
© Nick Hall

enacted to limit dry-season irrigation led to a narrower window between rice harvest and wheat planting, which inadvertently contributed to large-scale crop residue burning to quickly prepare fields for wheat.

At peak burning periods, agriculture burning contributes around 30% of fine particulate matter in New Delhi, the capital, where it causes respiratory harm, contributes to climate change, and disproportionately affects the poor who are less able to take adaptive measures.

FOODSCAPES ARE LINKED THROUGH GLOBAL SUPPLY CHAINS

Though foodscapes are each distinct, many are connected through global supply chains. This interconnection means that the potential for nature-based solutions in one foodscape is partially determined by actions in other geographies.

For instance, one of the biggest factors pushing almond producers in the Granada foodscape (Spain) to produce organic almonds is their inability to compete with the relatively cheap, irrigated almonds from the San Joaquin Valley foodscape (United States). In addition, the soy crushing facilities in the Chesapeake Bay Watershed foodscape process soy from the Argentina Gran Chaco foodscape when local soy is not available. Because of the dynamic nature of commodity trading, supply chain actors who want to support sustainability must ensure sustainable sourcing across their entire supply chain. Because supply chains contain different types of firms, from buyers to processers and retailers, there is need for a new era of within-supply chain collaboration and accountability on environmental sustainability.

PUBLIC AND PRIVATE BENEFITS PROVIDED BY TRANSITIONS ARE GREATER THAN THE COSTS, BUT THAT DOES NOT ALWAYS MEAN FARMERS WILL PROFIT

In most of the case studies with economic analysis, the costs of transition to nature-based solutions could be as high as, or higher than, current farm revenue. This level of transition cost will require outside investment. However, even though costs of transition are high, the public and private benefits provided by such transitions are greater than the needed investment cost. This does not mean, however, that farmers will always benefit financially. In the San Joaquin Valley foodscape, the agriculture sector will lose significant short-term revenue as a result of groundwater use restrictions. Nature-based solutions can help lessen those losses and may even provide some benefits, such as climate resilience through less dependence on variable water resources, as well as improvements in air quality, water quality, and more access to open space.

The Economics of Transition

Several of the foodscapes in Focus quantify the costs and benefits associated with the nature-based solutions associated with "production archetypes" that represented typical production systems for a given foodscape. In most cases, three or four archetypes were developed for each foodscape, covering the majority of the area and allowing extrapolation from farm to foodscape.

For each archetype, basic parameters were defined (size, primary commodities produced, yield, etc.). To assess production costs and benefits, typical unit costs were employed based on local data and corroborated via expert opinion. For external items (e.g., public costs and benefits), we either estimated the magnitude in native units (e.g., liters of irrigation water saved, tons of GHG mitigated) or used benefit transfer to assign an economic value.

In all cases, costs and benefits external to the market were reported separately from those that might appear in a producer's or local government's financial accounts. For each nature-based solution, the estimated impact on productivity and producer economics was derived from local literature and corroborated by expert opinion. In each case study, report writers highlight some of the high-level takeaways from the analysis.

The full details of each analysis, including detailed results, tables, methods, and data sources, can be found in the Supplementary Material. Reference

FOODSCAPES IN FOCUS

Aerial view of
Pilcomayo watershed,
Argentina
© Proyungas

Argentina Gran Chaco

Foodscape

Halt biodiversity loss through mixed land use

ARGENTINA

LOCATION: Northern Argentina
SIZE: 7 million hectares

SYNOPSIS

Argentina Gran Chaco foodscape, part of the larger Gran Chaco region of South America, has long accommodated a mix of uses, including hunting, grazing, and cropping in a region with high endemic biodiversity. Over the last 30 years, however, global demand for soy and beef has driven the destruction of millions of acres of native habitat and forests and led to rapid and large-scale simplification of this vast, complex landscape.

Such land use conversion – driven largely by demand for soy production – has obvious consequences for biodiversity but also creates risk for the production of food. Forest clearing, for example, leads to greater rates of soil erosion, flooding, and salinity in croplands. In Argentina, the national government approved a Native Forest Law that limits where land conversion is allowed, but illegal deforestation still occurs in response to strong market demand.

GRAND CHACO

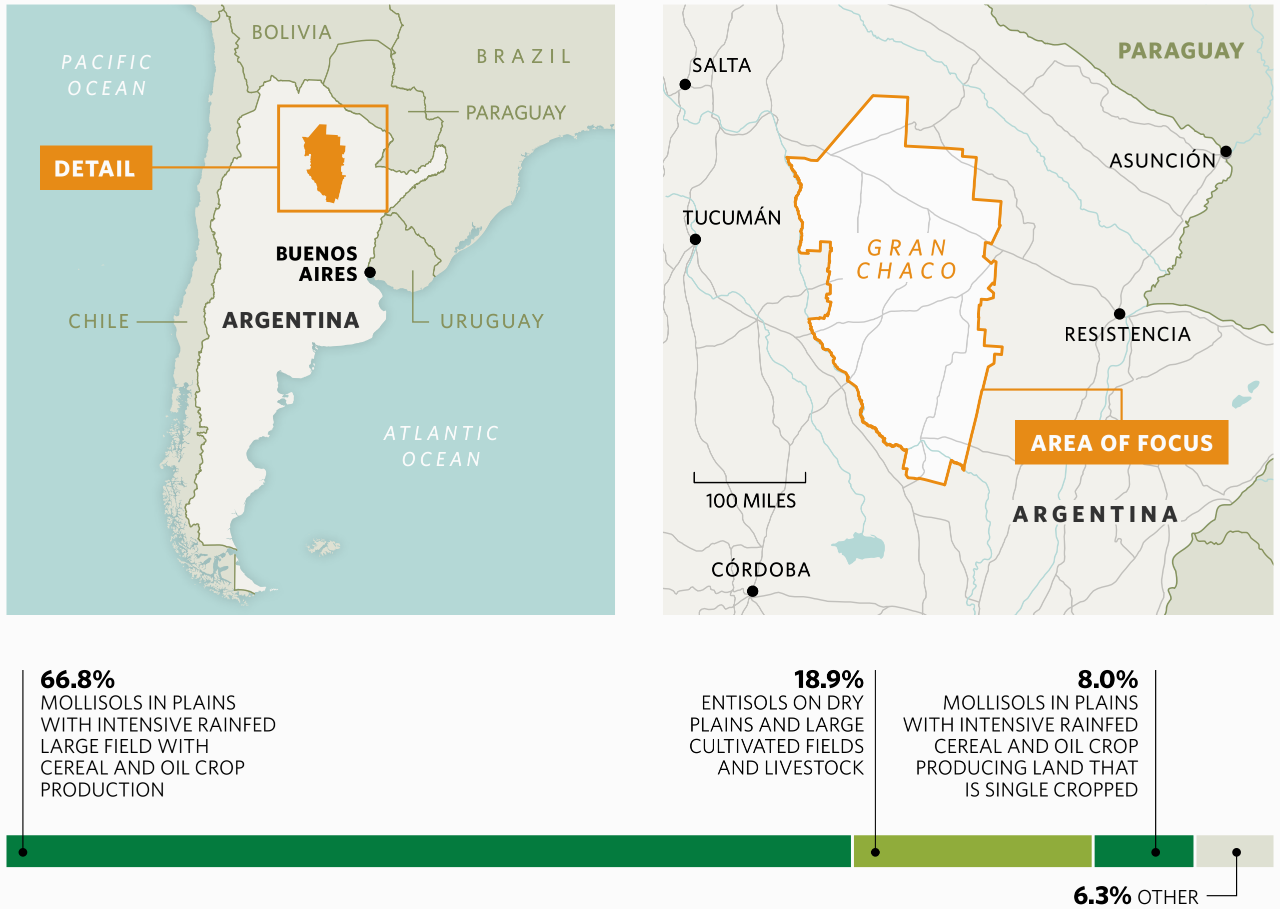


FIGURE 1. Map of Argentina Gran Chaco foodscape. The bars represent the most extensive foodscape classes within the foodscape. The color of bars indicates the intensity groups corresponding to those classes: intensive production dominant (dark green) and mixed mosaic food cultivation (light green). The other category includes the classes that each made up <5% of the foodscape area.

Nature-based solutions to land conversion, such as the adoption of agrosilvopastoral techniques – the combination of growing trees, crop production, and grazing cattle – offer the potential to protect Gran Chaco's traditional mixed-use landscape while still producing its economically important commodities and protecting its globally important biodiversity.

Widespread adoption of policies and practices, including nature-based solutions, to protect the integrity of Argentina Gran Chaco foodscape requires partnership with the agribusinesses sourcing commodities from this region. This highlights the greatest challenge and opportunity for the Argentina Gran Chaco foodscape: the development of coordinated policy and incentive systems that simultaneously promote the use of diverse practices to foster positive environmental, economic, and social outcomes across a diverse, complex landscape.

DESCRIPTION OF FOODSCAPE

The term *chaco* is suggestive of what makes this foodscape unique. In Quechua, *chaku* means vast hunting area, highlighting that the Gran Chaco has long been defined by multiple land uses that had wildlife living side by side with human use. The

Cattle grazing in the
Gran Chaco, Argentina
© Karina Diarte

broader Chaco, encompassing parts of Argentina, Paraguay, and Bolivia, was a politically cohesive entity up until the mid-19th century. The juxtaposition of rich biodiversity, multiple human land uses, and cohesive regional identity is still a key feature of the Chaco region today.

> The entire Gran Chaco is vast and contains part of the Chaco-Pampean Plain, one of the biggest plains on Earth. The Chaco's climate gradient gives rise to a diversity of habitats, from humid forest to dry forest, relatively open grassland, wetland areas, and gallery forests. The Chaco owes its long history as a hunting ground to its high faunal diversity and abundance. Because of the diversity of habitats, key species of the Gran Chaco include those common in humid forests, such as jaguar and tapir, and those common in dry areas including armadillos. The Argentinian Chaco – where the Argentina Gran Chaco foodscape is located – is the global peak of armadillo diversity, with some species only found within the foodscape boundary.

Alongside a diversity of habitats, the larger Gran Chaco landscape includes production systems that range from smallholders focused on local consumption to the large-scale production of grains and animal feed for export markets. However, until relatively recently, large-scale agriculture had historically been pursued primarily in a small area.

But starting in the mid-1990s, growth in local and global demand for beef, feed grain, and biofuels resulted in a dramatic acceleration of agricultural expansion. The Argentina Gran Chaco foodscape represents the most active area of land conversion and includes the boundaries of Argentina's Santiago del Estero, Chaco, and Santa Fe Provinces (FIGURE 1).

CHALLENGES

Since 1976, more than 26% of the dry Chaco has been deforested – an area of around 12 million ha. An additional 1 to 2 million hectares of new conversion are projected to occur by 2030. The majority of land conversion is due to soy expansion. Cattle production has also increased steadily with the majority being cow-calf operations that supply finishing operations farther south, outside of the foodscape. The expansion of livestock has led to forest cover loss as well as degradation of grassland and savanna zones.

Land use conversion threatens biodiversity as well as the productivity of agriculture itself. On the sandier, arid soils of the western Chaco, soil erosion is a major issue. Deforestation also leads to greater soil flooding and increased salinity; native vegetation is lost and evapotranspiration rates decrease, which increases the height of the water table. In some cases, this leads

Livestock in the shade in the Gran Chaco, Argentina
© Karina Diarte

to greater accumulation of salts in surface soils, with severe negative impacts on crop productivity. Flooded and salty areas are increasing inside the cropped zones, and farmers are more aware of this problem.

Only about 3% of the Argentinian Gran Chaco foodscape is part of formally protected areas, making conventional environmental protection a limited mechanism for addressing land conversion. The main effort to reduce land conversion is the Native Forests Law, national legislation developed by a consortium of partners and adopted in 2007 to regulate deforestation. This law does not ban forest conversion; instead, it limits conversion in certain areas while allowing it in others.

This means that many landowners have the legal right to carry out further land conversion. In addition to legal land conversion, illegal deforestation still occurs, mainly driven by demand for agricultural commodities such as soy. Because of this ongoing deforestation, current laws alone are insufficient to halt and reverse land conversion in Argentina's Gran Chaco foodscape.

BENEFITS AND VALUE OF NATURE-BASED SOLUTIONS IN ARGENTINA'S GRAN CHACO FOODSCAPE

The challenges within Argentina's Gran Chaco foodscape reflect similar challenges in other parts of the Gran Chaco as well as other parts of the world where increasing profits from commodities drive more and faster land conversion. The adoption of nature-based solutions, such as sustainable cropping and ranching practices, can mitigate biodiversity loss associated with land conversion by incorporating native vegetation into production landscapes. These practices can also help restore land that has been degraded through long-term production.

In grazing systems, incorporating rotational and/or silvopastoral grazing into grasslands increases livestock productivity and minimizes land degradation. Within Argentina's Gran Chaco foodscape, such practices could increase profits by an additional $3,550 per year for an average farm of 700 ha (Supplementary Material, Archetype A).

In mixed livestock-cropping systems, adding forest buffers and silvopasture to cropped areas – as well as adding cover crops to fields – creates an opportunity to increase net production and provide habitat value. Such a system could increase farm profits two-fold, from $278,000 per year for a 2,000 ha farm to $557,000 per year (Supplementary Material, Archetype B).

There is also opportunity for additional revenue streams from the incorporation of natural vegetation, such as carob flour and honey production. Doing so could increase revenue by 50% for small livestock farms that diversify from grazing only to mixed grazing, silvopasture, and honey production in restored forests (Supplementary Material, Archetype C).[1]

Across the Argentina Gran Chaco foodscape, mixed land use practices could nearly double farm income, though the costs of transition would be more than current farm profit and would thus require new sources of farm capital (FIGURE 2, p). Efforts to expand adoption of these nature-based solutions within the foodscape are ongoing with a primary focus on providing technical support to farmers and ranchers who may be unfamiliar with these practices.

On the policy side, strengthening legilation may also help reduce illegal conversion, but this will likely not halt it entirely, especially since illegal conversion remains profitable and enforcement across such a vast area is extremely difficult. Nature-based solutions that create a productive mixed-use landscape at the foodscape level – including biodiversity protection – offer the potential for a productive agriculture system that also creates habitat for the Chaco's plants and animals, from the abundant to the rare.

Enacting this vision requires collaboration with the private sector, which shapes its sourcing approach to create an economic signal for land managers using sustainable practices. The Vision Sectorial para el Chaco is an example of such an approach where environmental nonprofits and soy traders have collaborated on a vision of how to reduce deforestation.

Giant anteater pup at La Paya National Park, Argentina
© Hugo Arnal/TNC

AGGREGATION OF ARCHETYPES TO THE FOODSCAPE LEVEL

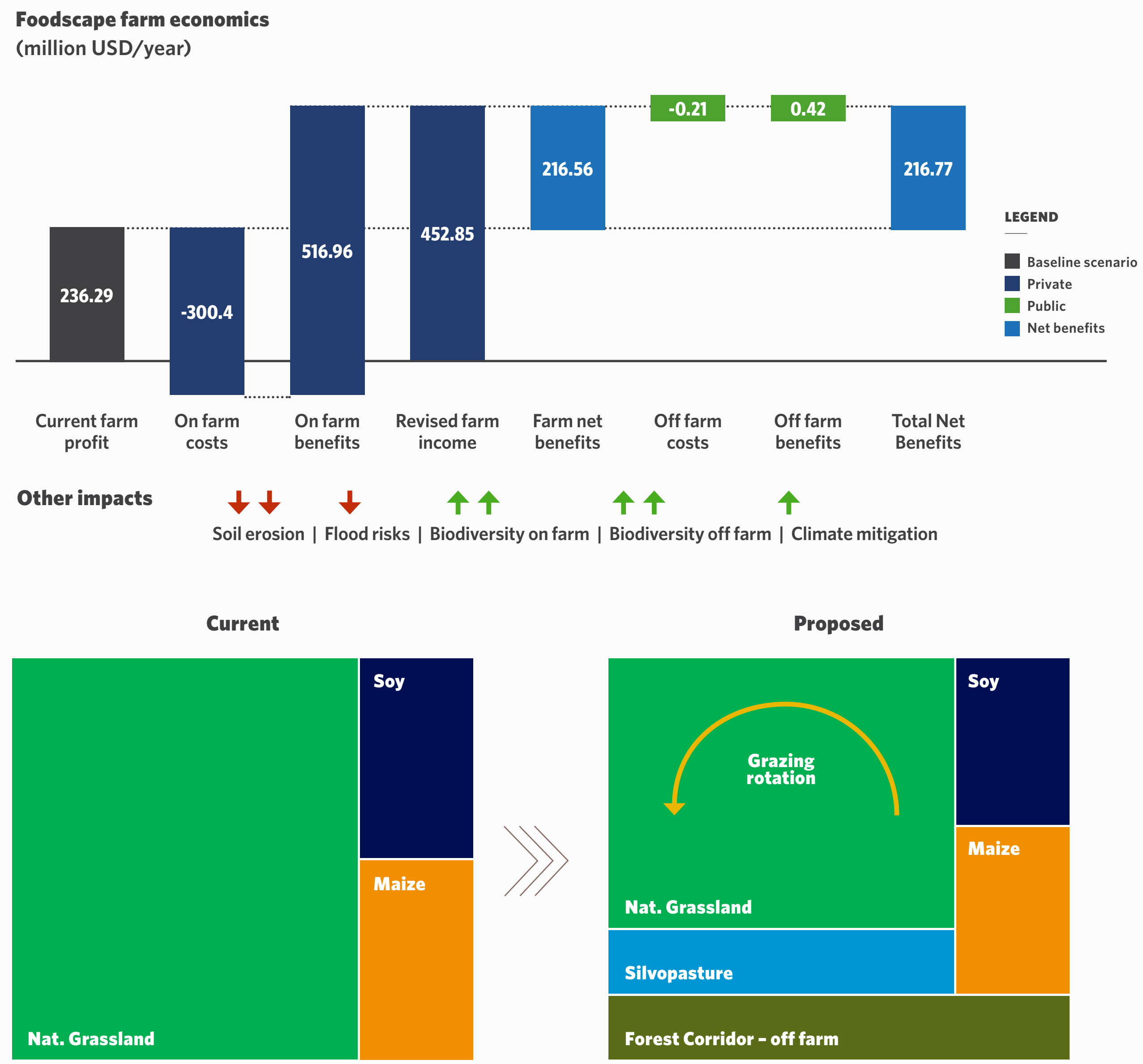


FIGURE 2. Summary of economic analysis for Argentina's Gran Chaco Foodscape. **Disaggregated costs & benefits toward $216 million net benefits from several farm archetypes:** Starting with baseline current farm profits (grey, far left), the diagram shows proposed future on farm benefits and costs (dark blue), totaling farm net benefits of $US 216.65 million (light blue, middle). Additional public off farm benefits and costs (light green) added to and subtracted from farm net benefits equals $US 216.77 million total net benefits (light blue, far right). Other impacts are qualitative assessments of other ecosystem service benefits. The change in area of nature-based solutions associated with the farm archetypes is represented in the boxes. See Supplementary Material for a description of methods.[1]

A young boy on horseback minding his family's herd of goats, Mongolia © Nick Hall

Arkhangai
Foodscape

Community-based conservation to protect rangelands

MONGOLIA

LOCATION: Mongolian Steppe
SIZE: 5.5 million hectares

SYNOPSIS

Rangelands are the planet's most widespread terrestrial ecosystem and support carbon storage, water, habitat for wildlife and pollinators, and forage for livestock. Grasslands and rangelands are home to 30% of the global human population and directly support the livelihoods of some 500 million pastoralists and ranchers.

Pastoralists hold traditional ecological knowledge embedded in their cultures, institutions, and daily herding practices, enabling sustainable use of these semi-arid, variable, remote, and often rugged landscapes. Global and regional environmental and socioeconomic changes threaten rangelands, pastoralist lifeways, and the values they provide to humankind.

The Mongolian *aimag* (region) of Arkhangai is a pastoralist foodscape in the Mongolian steppe that supports a large population of seminomadic pastoralists and is experiencing degradation both through increased grazing pressure and climate change. Community-based conservation that creates land rights for herders can help limit degradation and enhance pastoralist livelihoods while conserving rangelands and biodiversity.

ARKHANGAI

FIGURE 1. Map of Arkhangai foodscape. The bars represent the most extensive foodscape classes within the foodscape. The color of bars indicates the intensity groups corresponding to those classes: scattered cropland and grazing (yellow). The other category includes the classes that each made up <5% of the foodscape area.

DESCRIPTION OF FOODSCAPE

In Mongolia, rangelands account for 70% of the country's land area[2] that directly support the lifeways of 300,000 seminomadic pastoralists, roughly 10% of the population. Half of the country's inhabitants benefit from the economic activity generated from pastoralism. The most common livestock pastoralists herd across the steppe are sheep, cows, yaks, goats, and horses.

Experienced herders here seek to harmonize livestock needs with daily, seasonal, and interannual changes in plants, weather, and water availability. In practice, herders in the Arkhangai foodscape, like those in the rest of Mongolia, follow repeated patterns of seasonal movements among customary winter, spring, summer, and autumn pastures with a goal of meeting the changing physiological demands of their livestock with the most suitable available resources.[3]

A young girl milking her family's herd of dairy cows , Mongolia © Nick Hall

Mongolia's grasslands encompass three major ecological zones, the mountain-forest-steppe, steppe, and desert-steppe, as well as multiple unique ecosystems. The Arkhangai foodscape is representative of habitat for iconic and endangered species including red deer, Siberian Ibex, and musk deer; birds such as the Steppe Eagle, Saker Falcon, and Eurasian Spoonbill; and carnivores such as the snow leopard, grey wolf, Eurasian lynx and Pallas's cat.

Mongolian pastoralists have experienced significant transitions in modern history. During the socialist regime (1921–1992), livestock were managed under a collective system. Herders were paid employees of the state herding cooperative systems, which provided production inputs and support as well as social services that offered herders a relatively high quality of life. Collectives also governed pasture use, setting stocking rates, allocating pastures, and directing seasonal movements.[3]

The shift to a democracy and a market economy in the early 1990s marked notable changes to Mongolia and its rangelands, affecting herder well-being, rangeland governance, and resulting pasture conditions. State collectives were dissolved and livestock were privatized and allocated to individual herders. Local governments were charged with regulating pasture use and enforcing traditional norms such as setting aside grazing reserves for use in winter, but in practice local officials lacked the political will or resources to enforce laws.[4]

CHALLENGES

Thirty years of Socialist rule had eroded trust and customary norms to the extent that they were largely ineffective. Livestock privatization, combined with weak formal governance and the absence of pastoral institutions, led to increasing poverty and wealth disparities among herder households[5] and declining herd mobility.

There were also increases in year-round and out-of-season grazing (or "trespassing") on reserved winter pastures[6] as herd numbers grew. These factors led to conflicts over pasture and water and growing concern about herder well-being and rangeland conditions. Many of these stressors continue to affect food systems today through their influences on pastoralists and sensitive grassland ecosystems.

The Arkhangai foodscape is in the north-center of Mongolia, to the west of the capital Ulaanbaatar, where human modification of rangelands has been more intense than in other parts of the country. Livestock density in Arkhangai is higher than in most other parts of the country.

The socioeconomic drivers of change here have been exacerbated by climate change. Landlocked and far from the natural climate regulation provided by oceans, temperatures in Mongolia have already risen by over 2°C in the past 50 years and are expected to increase 6°C by the end of the 21st century.

A view from a mountain top above Khan Khentii Protected Area. Khentii *aimag*, Mongolia © Nick Hall

Rains now occur later and with more temporal and spatial variability, leading to decreased grassland productivity.[7] With greater frequency of droughts, pasture plants are not present during the expected season and are patchier, increasing risk of livestock mortality.[8]

Drought and overgrazing have also contributed to more severe *dzuds*, a term for a severe winter in which a large number of livestock die. A single *dzud* in the 2009–2010 winter killed more than 10 million livestock across the country (23.4% of the total herd).[9]

While human populations have declined in rural areas, the total number of livestock has increased, and herd compositions have shifted toward a greater proportion of goats, which are particularly damaging to grasslands. The combination of socioeconomic and climatic factors has led to a 32% decline in the number of herders since 2000.

Women and girls increasingly leave the countryside to seek higher education and a professional career in urban areas. These trends in turn affect family dynamics[10] and diminish the likelihood of transmitting and maintaining traditional ecological knowledge and lifeways over generations.

The social organization of herding is shifting, with more absentee-owned livestock and an increase in contract herders taking the place of owner-operators of family herding enterprises.[11] Growing and increasingly concentrated livestock populations coupled with declining herd mobility and a changing climate increase rangeland degradation, including potentially irreversible changes in plant community composition, productivity, and soil retention.

Given these trends, linked ecological and cultural tipping points could occur if overuse by livestock reduces productivity and increases vulnerability to severe winters, thus leading to a wave of rural-urban migration and accompanying loss of herding knowledge and cultural identity.[12]

Given the prominence of livestock for food systems and for broader commercial enterprises, integrating sustainability considerations into social and economic systems can incentivize and shape grazing practices on sensitive grasslands within the Arkhangai foodscape.

SOLUTIONS

The community structure is an important unit for traditional herders. In particular, community-based conservation is a set of approaches emphasizing the role of communities in managing their natural resources, and it often includes a set of practices, including nature-based solutions, that range from facilitating the formalized devolution of rights to communities, to enabling the co-management of resources and co-learning among communities, state, and nonstate actors.

Since the late 1990s and early 2000s, Mongolian community-based conservation has proliferated, with several international donors and NGOs/ENGOs supporting Mongolian herder communities as Community-Based Organizations to support formal recognition of sustainable rangeland management. By 2006, more than 2,000 groups were organized with assistance from 14 different organizations.[33] The Law on Environmental Protection of Mongolia in 2012 enables Community-Based Organizations members' rights to the resources on their customary lands, including management of forests and wildlife.

Within the Arkhangai foodscape, there are newly emerging Community-Based Organizations managing designated Local Protected Areas. Khoid Mogoin Gol-Teel Local Protected Area (137,000 ha) in Bulgan soum is managed by the Union of Conservation Communities; herders managed to stop poaching there and achieved a dramatic reduction in illegal logging, which resulted in a population increase of marmots (36%), Saker falcon (21%), and Steppe eagle (38%) against the baseline three years ago.[13]

Several studies have also found significant positive impacts of community-based conservation efforts on human and environmental outcomes in Mongolia,[14-16] including addressing resource management issues, strengthening social networks, and using traditional and innovative rangeland management practices.[36] These positive behavioral changes were also associated with many benefits to the communities, including access to more information sources, stronger leadership, more opportunities for knowledge exchange, clear and enforceable rules for resource use,[17] and enhanced adaptive capacity in the face of climate hazards.[18-19]

Strengthening these institutions is a priority for managing the dynamic and shifting demographic, climate, economic, and political conditions that currently threaten Mongolian rangelands now and into the future.

Port Underwood, Marlborough Sounds Museel Farm near Horahora Kakahu, New Zealand © Rob Suisted

Central New Zealand Aquaculture
Foodscape

Aquaculture diversification for resilience

NEW ZEALAND

LOCATION: New Zealand

SYNOPSIS
Central New Zealand is one of the largest shellfish producers in the world. In addition to supplying global markets, seafood has played a central role in the culture and foodways of indigenous communities for centuries. Yet, the Central New Zealand Aquaculture foodscape has limited space to expand operations in near-shore areas, constraining the opportunity for growth in this highly sustainable food source, and is also vulnerable to environmental and economic shocks because of its focus on a relatively small number of species.

Open-water and near-shore restorative aquaculture provide an opportunity to increase the productivity and resilience of the foodscape by adding a seaweed sector to diversify production. But despite strong potential for diversified aquaculture within the foodscape, there is still need to develop both the markets for diversified products and the infrastructure needed for this approach to be effective at scale. In the case of seaweed, barriers to human consumption likely need to be addressed more broadly, including public perceptions around food safety and the viability of seaweed as a dietary staple.

CENTRAL NEW ZEALAND

FIGURE 1. Map of Central New Zealand Aquaculture Foodscape.

In terms of infrastructure development, emergent programs already highlight the potential for regional partnerships to catalyze sector-wide development, such as Seaweed for Europe.[20] These programs provide a valuable analogue for collaboration on shared challenges and offer learnings in the development of markets and technology, in this foodscape, in New Zealand more broadly, and across other marine foodscapes and regions.

DESCRIPTION OF FOODSCAPE
Mariculture – aquaculture in marine environments – in the Central New Zealand Aquaculture foodscape (FIGURE 1) takes place in three ecoregional provinces that span the main islands (northeastern, central, and southern New Zealand) and a range of sheltered and exposed, subtropical, temperate, and subarctic environments.[21]

Aquaculture production has averaged 107,097 tons per annum from 2010 to 2020, with production comprised of a total of four shellfish and finfish species valued at more than $800 million. Approximately three-quarters of the country's mussel production (green-lipped mussel, *Perna canaliculus*) and two-thirds of fin-fish production (King salmon, *Oncorhynchus tshawytscha*) occurs in this foodscape. Currently, more than 600 farmers make up the green-lipped mussel industry, many of which farm an area less than 10 ha in size, often as small as 3 ha.

Kaimoana (seafood, in Māori) has always been an important source of protein and cultural and spiritual connection for coastal Māori. Māori traditionally carried out aquaculture activities, and the Waitangi Tribunal resolved that Māori have a customary interest in this activity; this is a finding that formed the basis for an allocation of 20% of new marine farming space to Māori a 2004 settlement.

Green-lipped mussel farm (*Perna canaliculus*), marine farming in Admiralty Bay, Marlborough Sounds, New Zealand.

The cultural importance of *kaimoana* has grown as the availability of the other main traditional protein source, birds, has been restricted by law and scarcity. An estimated 40% of the marine farming industry is now owned by Māori.

CHALLENGES

Access to nearshore mussel farming sites has become limited in important growing areas such as the Marlborough Sounds. This is due to multiple factors, such as physical limitations on space, the need to work within the limits of regional ecological carrying capacity, and the need to ensure negative environmental impacts do not occur.

Social expectations also affect the support that is given to a sector or company, influencing the potential for aquaculture to occur and under what circumstances (e.g., types of farming, proximity to shore, license requirements). The type of farming (finfish versus shellfish), the quality of an individual's contact with an aquaculture operator, the potential for cultural impacts, and perception about the fairness of how economic benefits are distributed have been identified as influential in public acceptability of the aquaculture industry.[22]

At the same time, the health of ocean environments and impacts from land-based nutrient and sediment inputs, which must be managed by industry aquaculture operations, continue to be persistent issues in coastal and marine areas.[23]

The lack of diversity of products within Central New Zealand's Aquaculture foodscape exposes food producers here to a range of biophysical (e.g., climate change), market (e.g., fluctuations in price and demand), and social (e.g., changing social preferences) risks.[24,25] The foodscape's essential vulnerability was recently exposed under COVID-19 when foreign markets for mussels became limited, leading to an estimated 20% decrease in mussel prices, challenging the profitability of many farming operations.

Mussel farmers and industry associations that represent them have become increasingly interested in integrating seaweed farming into existing mussel leases. Seaweed aquaculture represents an opportunity for the industry to diversify the production portfolio, supplement incomes, increase their resilience to future change, and enhance the provision of ecosystem services from aquaculture operations.

With a concerted focus on overcoming barriers to seaweed aquaculture production and markets, the Central New Zealand foodscape could support profitable and sustainable, diverse aquaculture operations, including seaweed farming.

SOLUTIONS

The Government of New Zealand has outlined a vision to become a "globally recognized world leader in sustainable and innovative aquaculture across the value chain"[26] and has a stated goal of expanding to a $1 billion industry by 2025. The government also recognizes the specific opportunity for aquaculture to "be a more significant part of a lower emissions economy."

The first of four outcomes listed in the national government's aquaculture strategy is environmental sustainability, which suggests nature-based solutions, such as restorative aquaculture, will be foundational to improvements and expansions in the aquaculture industry.

The strategy further emphasizes the need for innovation, including the diversity of production and development of new production technologies to support sustainable aquaculture, such as seaweed farming and open ocean aquaculture.

Economic modeling has assessed the theoretical addition of seaweed farming of kelp, *Ecklonia radiata*, under two transition scenarios in the Marlborough Sound within the Central New Zealand foodscape (one of the most favored and high-density farming areas in New Zealand). One scenario focuses on a 5 ha mussel farm integrating seaweed in its farming operations alone, and the other focuses on a farm that integrates seaweed in its operations while being part of a cooperative that jointly owns the seaweed nursery and processing facilities.

In the first scenario, mussel farmers could increase income through integration of seaweeds, by an estimated $35,000 per year. If farming activities are vertically integrated, including a hatchery for production of seed through a cooperative approach as in scenario two, it is estimated that income would rise significantly, to $82,000 per year, a 133% increase over farming individually (FIGURE 2).

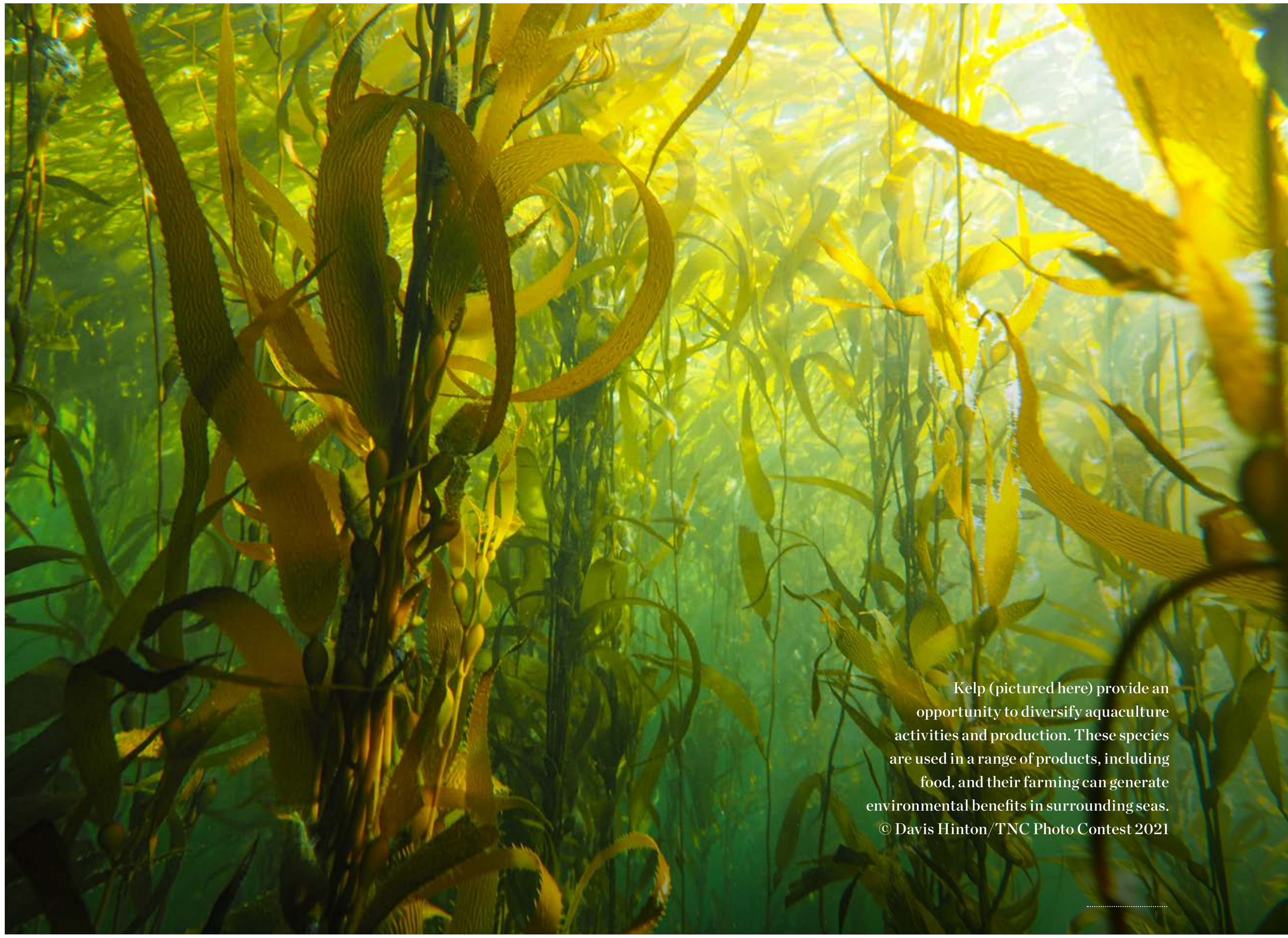
The environmental benefits associated with this vertical approach would also increase. As non-fed, extractive species, bivalves and seaweeds have the greatest current known potential for restorative aquaculture. These species groups can improve water quality at various scales because they remove nutrients, including nitrogen and phosphate.[27,28]

In fact, a global opportunity assessment for restorative aquaculture potential identified the three marine ecoregions surrounding the mainland coasts of the north and south islands as "high" opportunity areas to profitably generate positive environmental outcomes through seaweed and shellfish farming.[29]

Longer term, restorative aquaculture might also provide the opportunity to engage with greenhouse gas emissions reduction of farming operations and abatement strategies for other industries, such as through the use of seaweed for production of biofuels or biochar (to improve soil carbon sequestration). By integrating seaweed into farming operations, it is estimated a 5 ha mussel farm could reduce greenhouse gas emissions by 1.7 tonnes of CO_2 equivalents per year and absorb an additional 0.34 metric tonnes of nitrogen from coastal waterways.

Integrating seaweed and shellfish farming can also provide nature-based solutions to help address some of the environmental challenges now facing New Zealand waterways, including persistent eutrophication due to agricultural runoff and coastal development, as well as habitat declines of native kelp and mussel beds. Seaweed and shellfish filter water and cycle nutrients, which can contribute to reductions in excess anthropogenic nitrogen, phosphorous, and carbon.

Seaweed farming can create a localized effect in buffering pH and increasing acidification,[30] and spillover of mussel larvae from aquaculture can supplement wild mussel populations that may have declined.[31] In association with farming infrastructure these species also provide habitat for a range of other wildlife, especially fish and invertebrates, which come to these areas for feed or shelter, including shelter for recruitment.[32,33] Diversifying the species farmed, and engaging specifically with farming of seaweeds, provides a pathway for the New Zealand aquaculture industry to increase efficiencies in the use of current allocations of water; increase income at the farm scale, enhancing the socioeconomic value of the industry; plan for longer term impacts, such as climate change, and related shifts in biophysical parameters; reduce risk associated with diseases and pathogens (typically species-specific) as well as external shocks in trade (e.g., fluctuations in commodity price); and more confidently approach changing expectations in social license, governance, and marine planning.



Kelp (pictured here) provide an opportunity to diversify aquaculture activities and production. These species are used in a range of products, including food, and their farming can generate environmental benefits in surrounding seas.
© Davis Hinton/TNC Photo Contest 2021

Agricultural landscapes can impact coastal aquaculture through farming practices, South Island, New Zealand © Michael Yamashita

AGGREGATION OF ARCHETYPES TO THE FOODSCAPE LEVEL

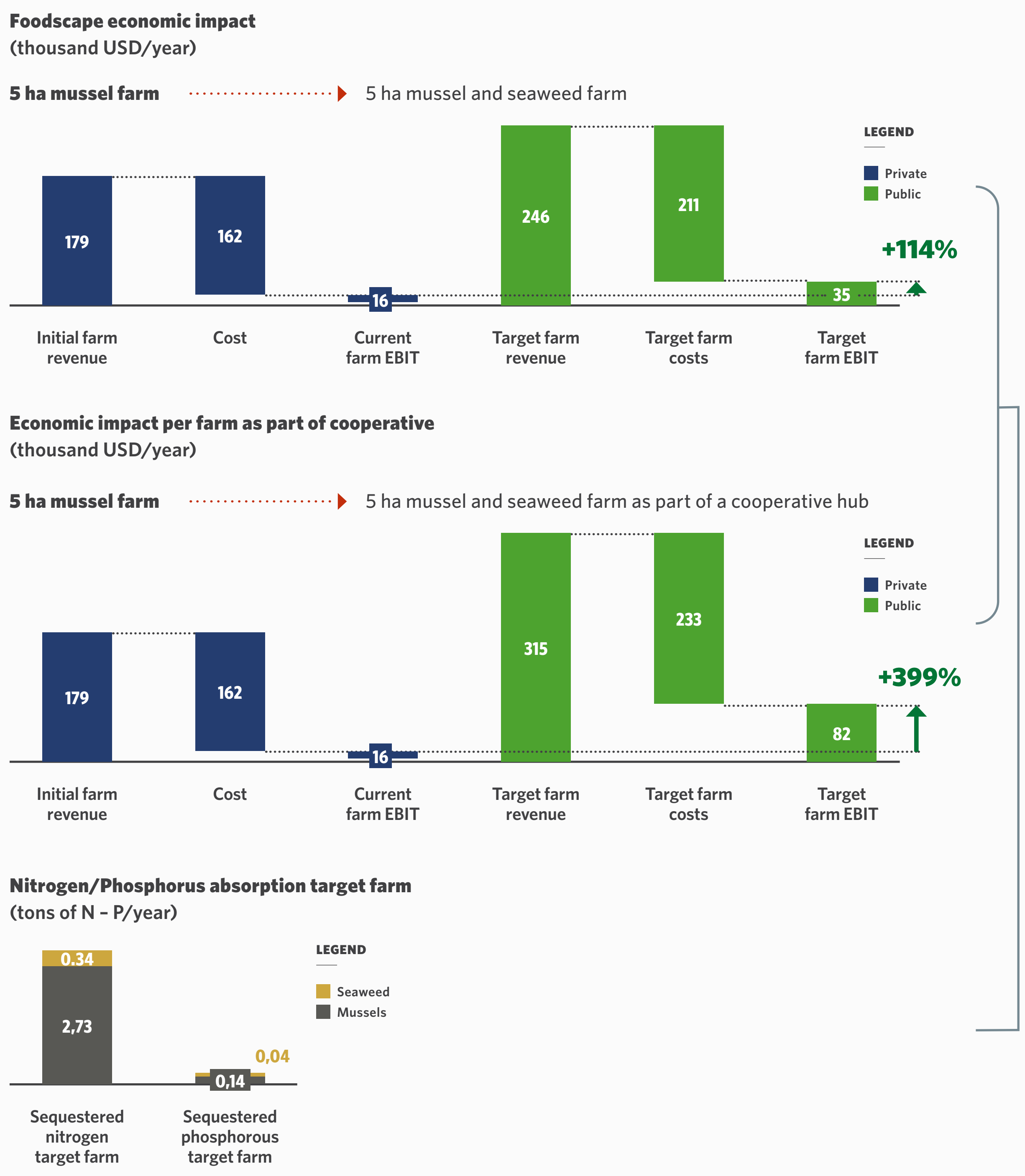
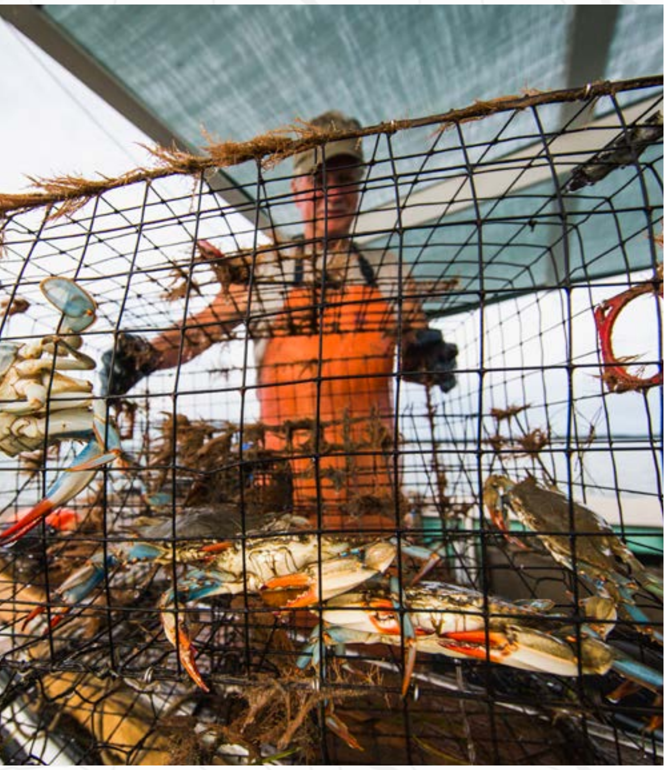


FIGURE 2. Summary of economic analysis of nature-based solutions in the Central New Zealand Aquaculture foodscape. The diagram describes the costs and benefits associated with two transitions in the integration of seaweed with mussel farming, a 5-ha mussel farm integrating operation alone, and a farm integrating as part of a cooperative (jointly owns the seaweed nursery and processing facilities). The waterfall diagrams summarize current farm costs and benefits, future farm costs and benefits, public costs and benefits, and total net benefits associated with the two scenarios. Estimated impacts on nutrient absorption apply to both scenarios. See Supplementary Material for a description of methods.[1]



Freshly caught crabs, Chesapeake Bay, USA
© Jason Houston

Chesapeake Bay Watershed
Foodscape

Restore natural habitats to enhance success of nutrient reductions

UNITED STATES

LOCATION: Mid-Atlantic, United States
AREA: 18 million hectares

SYNOPSIS

As its name indicates, the Chesapeake Bay Watershed foodscape spans terrestrial and marine environments and highlights the connections between the two. The Chesapeake foodscape helps frame the cause-and-effect relationship between upstream food producers and downstream consumers, but with a bit of a twist. In this foodscape, many downstream consumers are also food producers (seafood such as oysters and blue crabs) and their quality of life and their livelihoods are doubly threatened by excess nutrients flowing into the bay.

Looking at solutions to such a distributed problem from a foodscape perspective shows how new integrated approaches, including nature-based solutions such as oyster reef restoration, could significantly contribute to improving water quality by removing excess nutrients directly from the waters of the Chesapeake Bay and its tributaries.

CHESAPEAKE BAY

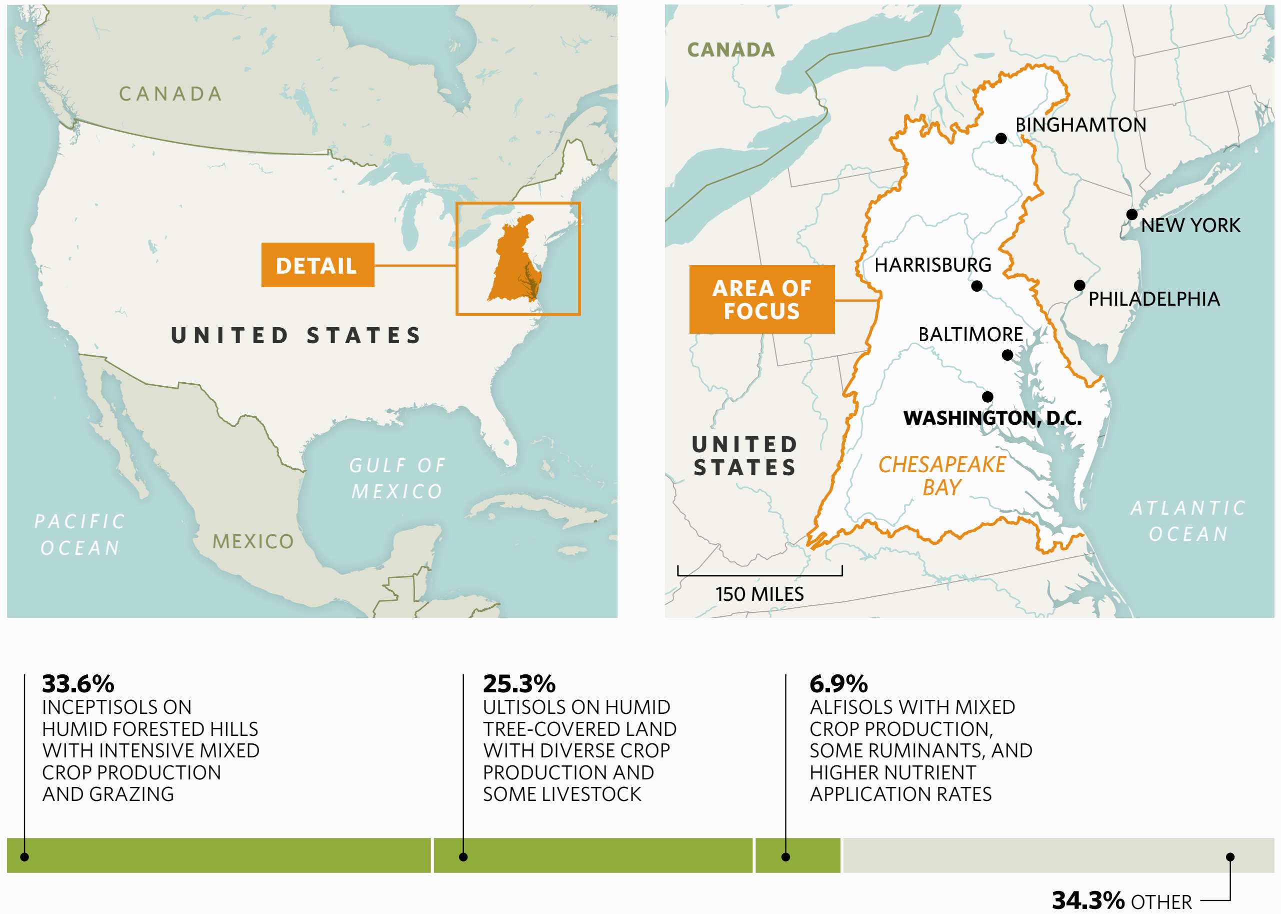


FIGURE 1. Map of Chesapeake Bay Watershed foodscape. The bars represent the most extensive foodscape classes within the foodscape. The color of bars indicates the intensity groups corresponding to those classes: mixed mosaic food cultivation (light green). The other category includes the classes that each made up <5% of the foodscape area.

Oysters are nature's water filter, and a single healthy adult can filter as much as 50 gallons of water a day. Still, as powerful as they are, restoring oyster reefs alone will not be enough for bay states to meet nutrient-reduction targets set by the federal government. Fortunately, the establishment of the Chesapeake Bay Watershed Agreement, a multi-state and multi-organizational partnership, created a unique framework for interstate action toward reaching those environmental goals. And the bay's health is improving.

Promising improvements in water quality to date are largely due to three factors: strong investment in science and the development of quantitative nutrient targets; several decades of action and investment, even before formal nutrient reduction targets were established; and political support and buy-in from the population of the watershed. Overlaying where enabling conditions and successful nutrient-reduction programs are in place across the foodscape could help decision makers pinpoint areas of maximum need and potential for meeting nutrient-reduction targets.

Ultimately, success in the Chesapeake will depend on a combination of regulations, public and private investment to support nature-based and other solutions, including environmental restoration, as well as the adoption of regenerative agriculture practices, and support from the broader supply chain to incentivize sustainable practices.

DESCRIPTION OF FOODSCAPE

The Chesapeake Bay Watershed foodscape is a complex system that provides a clear example of the need for multi-use planning and cooperation. Part of what makes the foodscape complex is its scale: it spans the states of Delaware, Maryland, New York, Pennsylvania, Virginia, and West Virginia (FIGURE 1).

The area is home to more than 18 million people in some of the East Coast's most densely populated areas. In fact, only 20% of the watershed is made up of agricultural land. That agricultural land itself is varied, ranging from smallholder Amish dairies in Pennsylvania and New York to larger-scale poultry and feed-grain operations on the Delmarva Peninsula.

In Delaware and Maryland, more than three-quarters of agricultural land is under row crops, whereas only one-third of the Chesapeake's agricultural land in Virginia and New York is under row crops. Terrestrial food production revolves around the poultry industry, dairy, silage and feed production for the poultry and dairy industries, and a smaller amount of vegetable and fruit production and cow-calf operations for beef.

The Chesapeake Bay itself is an important food producing landscape. Perhaps best known for the blue crab, the bay has also been an important commercial fishery for striped bass, oysters, shad, and menhaden. This rich marine foodscape is characterized by the relationship among several species along the food chain.

Underwater grasses that grow in the shallower areas of the bay provide habitat for young crabs, menhaden, and shad as well as vulnerable molting blue crabs. These younger fish are important components in the food chain for larger taxa such as striped bass in deeper parts of the bay. Thus, impacts on shallower, coastal zones have cascading effects on the broader health of the bay. Coastal wetlands and oyster reefs are also crucial for wildlife through the provisioning of habitat and the ability to filter sediment and runoff.

CHALLENGES

Excess runoff of nutrients (both nitrogen and phosphorus) and sediment is the defining challenge of the Chesapeake Bay Watershed foodscape. Agriculture in the watershed is the greatest source of nitrogen. Despite making up only 20% of the area of the Chesapeake Bay Watershed, agriculture contributes more nitrogen to the bay than any other sector.

When nutrients and sediment enter the bay, they fertilize algae that block sunlight from reaching underwater grasses and create low-oxygen conditions harmful to marine life. Because of the interdependence of the broader bay ecosystem on coastal zones, the suppression of life in the littoral zone cascades to the broader bay. In the past, dams along the Chesapeake Bay's largest tributary, the Susquehanna River, captured some of the sediment entering the bay. Those dams are now full, making nutrient and sediment management upstream even more important to meet water quality goals in the bay.

A farm using optimal nutrient management practices, Cordova, Maryland, USA
© Isaac Shaw

Though agriculture is the greatest source of nutrients and sediments, the impacts of urban and suburban areas on water quality are also significant, and they are the only nutrient source in the bay that is increasing. In the past, the greatest reductions in nutrient loading to the watershed have come through management of wastewater treatment.

Cities such as Washington, D.C., established standards on clean water that comprised nearly two-thirds of the total nutrient reductions in the bay between the mid-1980s and 2018 (the other third came from the agriculture sector). Future urban expansion has the potential to affect the foodscape in direct and indirect ways.

Directly, the expansion of impervious surfaces associated with urbanization is increasing runoff quantity, which increases nutrient losses. Also, nitrogen deposition from fossil fuel combustion – such as cars – is an important source of nitrogen throughout the watershed; these nutrients run off into water from all land use types. Indirectly, urbanization is increasing the value of land, which increases the likelihood of conversion of agricultural land to suburban and exurban development. Although the net effect of this conversion on nutrient balance is uncertain, it poses a threat to the foodscape in terms of maintaining a viable farming economy that also provides environmental benefits.

Although nutrient loading is the major driver of changes in the Chesapeake Bay, fisheries and marine life have also been strongly affected by habitat loss. Coastal wetlands in particular have been threatened by shoreline development, invasive species, and sea-level rise. The loss of these wetlands, similar to the loss of underwater grasses due to hypoxia, threatens the

Oyster farmer in the Chesapeake Bay,
White Stone, Virginia, USA
© Robert Clark

broader health of the bay. Throughout the watershed, 600,000 hectares of nontidal wetlands have been lost. These noncoastal wetlands are crucial to coastal functioning because they filter water running off the land into bay tributaries.

Oysters, an iconic bivalve in the Chesapeake, have also experienced major declines, and today they are at a tiny fraction of their historical population due to overfishing, disease, and poor water quality. Oysters and their reefs provide essential ecosystem services such as water filtration and critical habitat for other species; their reductions have meant the loss of these services in many parts of the bay. Successful restoration of large-scale reefs over the past decade and the emergence of aquaculture as a sustainable fishery provide hope for the future for this keystone species.

Blue crabs also represent an iconic species in the Chesapeake and are essential to the region's economy and ecology. The population of blue crabs in the Chesapeake for the past two decades has been below average, and management actions have attempted to address areas of vulnerability, including harvest pressure, pollution, and habitat loss.

Overfishing has also led to losses of key species and declines in the viability of fishing livelihoods. Striped bass, one of the most important species commercially and recreationally, declined sharply in the 1970s and underwent strong regulation until it was considered recovered in the mid-1990s. Though the population is considered recovered, striped bass are an apex predator in the bay and therefore are susceptible to ongoing fishing pressure and changes throughout the food chain. A less rosy story is that of shad, which was both an important fishery and an important source of food for wildlife. The shad population has been significantly affected by dams and associated habitat loss as well as overfishing.

BENEFITS AND VALUE OF NATURE-BASED SOLUTIONS IN THE CHESAPEAKE BAY WATERSHED FOODSCAPE

Although regional activities, including voluntary nutrient reduction targets, had existed here for years, the 2014 Chesapeake Bay Watershed Agreement, a multi-stakeholder collaborative partnership, was created after the U.S. Environmental Protection Agency set regulatory nutrient-reduction goals for the bay in 2010. The agreement is a holistic watershed management strategy that incorporates goals for fisheries, habitat, water quality, climate resiliency, and community engagement.

While significant progress has been made over the past 30 years, the region is not currently on track to meet 2025 nutrient reduction targets, largely due to funding constraints in key states and sectors. Changing farm management practices, for example, can offer potential opportunities for using nature to help remove nutrients at the source. Livestock operations could introduce silvopasture paddocks in pasture areas, expand cover crops to cereal fields, and add edge-of-field vegetation strips to filter nutrients before they reach nearby streams and rivers.

Such practices could provide a revenue increase of $49,000 per year for a farm of about 100 ha, or about a 50% increase in net profit (Supplementary Material,[1] Archetype A). Combining cover cropped cereals with nontidal wetland restoration and perennials could also increase net profit by about 15% (Supplementary Material,[1] Archetype B).

Incorporating edge-of-field habitats, developing nature-based stormwater management systems, and creating a manure market for poultry farms could increase net revenue by 1%, which is the equivalent of about $13,000 per year for a 4 ha farm (Supplementary Material,[1] Chesapeake – Archetype C).

Finally, combining the nature-based solutions of silvopasture, cover crops, and edge-of-field restoration across the entire Chesapeake Bay Watershed foodscape could increase net farm benefits by $206 million per year and provide $29 million per year in public benefits (FIGURE 2).

The increased adoption of both in-field and edge-of-field practices is essential to achieving nutrient reductions in the Chesapeake Bay watershed. Cover crop use has increased from nearly zero ha in the mid-1980s to close to 400,000 ha at present. Nutrient management and many edge-of-field practices, however, remain low. On the agricultural side, working with farmers' trusted advisors as well as traditional technical assistance providers, such as university extension and soil conservation districts, to ensure that farmers have access to information and technical support will be critical to adoption and continued use of new practices.

Planning at the foodscape level, may illuminate ways the broader supply chain could create incentives by sourcing commodities produced with practices that minimize nutrient losses and provide other ecosystem services, or by investing in farms within their supply chain to implement conservation practices. Agribusiness, such as fertilizer and seed retailers, provides important technical services to farms and could be an important contributor to increased adoption of nature-based and other nutrient-reduction practices.

Because water quality in the bay is so dependent on the health of its coastal habitats, restoration, the original nature-based solution, also has a critical role to play in reducing nutrients, erosion, and sedimentation. Across the Chesapeake Bay Watershed foodscape, there are immediate opportunities for restoring both tidal and nontidal wetlands under the Chesapeake Bay Watershed Agreement. RRight now, the agreement calls for reestablishing and restoring 55,000 ha of wetlands and 75,000 ha of underwater grasses.

Habitat restoration also extends to restoration of marine habitat. An emerging body of science has demonstrated the clear nutrient reduction benefits associated with oyster reef restoration.[34] Restoration of oyster reefs in the Chesapeake over the past decade has been the largest shellfish reef restoration on the planet, and this has delivered ecological and economic benefits through additional nutrient removal and enhanced production of fish and crabs that depend on these reefs for at least part of their life cycles.

Under the terms of the Watershed Agreement, oyster reef restoration will be included as an approved strategy for achieving nutrient reduction targets within the bay. This type of approach also demonstrates a nature-based solution that creates environmental benefits while also supporting a growing aquaculture industry within the foodscape.

AGGREGATION OF ARCHETYPES TO THE FOODSCAPE LEVEL

FIGURE 2. Summary of economic analysis of nature-based solutions in the Chesapeake Bay Watershed foodscape. **Disaggregated costs & benefits toward $114 million net benefits from several farm archetypes:** Starting with baseline current farm profits (grey, far left), the diagram shows proposed future on farm benefits and costs (dark blue), totaling farm net benefits of $US 206 million (light blue, middle). Additional public off farm benefits and costs (light green) added to and subtracted from farm net benefits equals $US 114 million total net benefits (light blue, far right). Other impacts are qualitative assessments of other ecosystem service benefits, except for soil erosion and nutrient runoff, which were quantified. The change in area of nature-based solutions associated with the farm archetypes is represented in the boxes. See Supplementary Material for a description of methods.[1]

A farmer prepares a field for planting at the Nehas Liah, Indonesia
© Bridget Besaw

East Kalimantan
Foodscape

Protect and enhance habitat through adaptive land use

INDONESIA

LOCATION: Borneo, Indonesia
AREA: 12.5 million ha

SYNOPSIS

The tropical forests of Borneo's East Kalimantan foodscape in Indonesia have been fragmented and degraded to meet ever-increasing global demand for logging, mining, and agricultural commodities. Additionally, the region has suffered catastrophic fires fueled in part by forest degradation. The profitable market for agricultural exports – primarily of palm oil – puts increasing pressure on unutilized or uncultivated land, like the remaining forested areas of East Kalimantan.

But even fragmented as they are, these forests serve a critical role for East Kalimantan's Indigenous cultures, biodiversity and climate stabilization.

To achieve a sustainable economic and environmental future, further deforestation must be reduced by directing cultivation away from remnant forest habitat and on to already degraded lands. Looking at potential solutions to the challenges in East Kalimantan through the frame of its foodscape could offer a path away from business-as-usual management by showing the potential shared benefits of better, more strategic land use planning partnerships between provincial government and local communities and organizations.

EAST KALIMANTAN

FIGURE 1. Map of East Kalimantan foodscape. The bars represent the most extensive foodscape classes within the foodscape. The color of bars indicates the intensity groups corresponding to those classes: little or only subsistence food production (beige) and mixed mosaic food cultivation (light green). The other category includes the classes that each made up <5% of the foodscape area.

DESCRIPTION OF FOODSCAPE

East Kalimantan, an Indonesian province on the equatorial island of Borneo, contains 6.8 million ha of some of the most biologically rich tropical forest in the world.

The terrain drives the different forest ecosystems and biodiversity found across East Kalimantan. Shorter montane forests are found in the mountainous, northern interior while *Dipterocarp* forests with tall hardwood trees and tidal forests, such as mangroves, occupy the lowlands. The region's climate is impacted by monsoons, creating distinct rainy and dry seasons.

More recently, El Niño events have contributed to extreme climatic conditions fueling severe drought and destructive fires. These more erratic events have also coincided with increased forest degradation from commercial land use within the foodscape.

Monitoring for wildlife in the Wehea forest, Kalimantan, Borneo, Indonesia
© Bridget Besaw

Across the island of Borneo, which also contains the Kingdom of Brunei as well as two states governed by Malaysia, there are more than 1,200 species of mammals, birds, amphibians, and fish, many of which are endemic, including the proboscis monkey, Müller's gibbon, and Bornean orangutan. Efforts around orangutan protection are especially prioritized in East Kalimantan as it contains 5% of the world's remaining wild population.

East Kalimantan has one of the lowest provincial population densities in Indonesia, due in part to the poor soil fertility and inaccessibility. Rich in raw materials, East Kalimantan's economy has prospered through mining and forestry exports. To accommodate the sloped terrain and poor soils, agriculture has been dominated primarily by plantations of rubber, coconut, and oil palm trees.

Of the three types of plantations within the foodscape, oil palm has been most heavily supported by the central government, and plantation areas have steadily expanded since the 1990s alongside global demand. Palm oil, the vegetable oil pressed from fresh oil palm fruit bunches, remains the region's main agricultural export.

To accommodate land conversion needs, the land is divided into designated forest and non-forest zones. The non-forest zones, which amount to roughly one-third of the total area of the East Kalimantan foodscape, account for all commercial and urban land use. Groups of smallholders and private companies are often organized into concessions within these non-forest zones for the production of the foodscape's major commodities.

Oil palm concessions account for 16% of the total non-forest land allocation in East Kalimantan. The remaining 8 million ha of designated forest zones ave varying levels of protection and are meant to remain natural forest. However, there is still a considerable amount of loss and degradation within forest zones from fire, illegal logging, and conversion outside concession boundaries, all of which continue to damage habitat quality and connectivity.

CHALLENGES

East Kalimantan has strengthened its economy through forest conversion for commodity production, but the losses and degradation complicate the future of this foodscape. More than 5 million ha of natural ecosystems here have been lost and around 13% of the remaining natural ecosystems are endangered.

While technological advances and resources are improving forest monitoring and enforcement, the remaining fragmented habitat areas are not cleanly organized within legally protected forest zones in the East Kalimantan foodscape. Orangutans have been spotted within oil palm and timber concessions, where it is legal to extract timber. Without a more complete picture of important conservation areas within non-forest zones, the onus lies on land managers to identify these habitats and manage for biodiversity conservation. Unfortunately, this reliance on land use managers creates disincentives for conservation because there is a significant and disproportionate opportunity cost associated with conservation actions within concession boundaries.

The remaining patches of forest degraded by intensive logging are another important consideration for the future of this foodscape. This forest system as a whole has some resilience, and non-isolated heterogeneous patches of degraded forest can recover with sufficient time; however, historic fires linked to El Niño events have shown there can be severe short-term consequences of increased forest degradation. The precise relationship between fire and El Niño is not yet fully understood, but as El Niño events bring warmer and drier conditions to Borneo, deforested and degraded areas appear to experience greater extremes, increasing the flammability of the forest and potential for tree mortality.

Beyond potential habitat and economic losses linked to fire, continued forest loss is a primary source of carbon emissions for East Kalimantan. Mitigating further losses is the region's most effective route to combatting climate change. The vulnerability of remaining degraded forest puts the province at risk for future consequential fire events without proper mitigation strategies.

BENEFITS AND VALUE OF NATURE-BASED SOLUTIONS IN THE EAST KALIMANTAN FOODSCAPE

In response to environmental concerns, several industries are making use of the high conversation value (HCV) definitions set by the HCV Resource Network in regions with land conversion pressures. These definitions provide a framework for identifying and protecting land from conversion if it is important for biodiversity, climate, culture, or other related values. Efforts are underway in East Kalimantan to map existing HCV areas, a critical tool for protecting remaining endangered habitats, particularly within non-forest zone concession boundaries.

A meal of freshly caught, stir-fried freshwater fish with local vegetables on the banks of the Sagah River, East Kalimatan, Borneo, Indonesia © Bridget Besaw

To address accelerating cultivation pressures within the foodscape, the provincial government of East Kalimantan is looking within forest zones for opportunities to use nature-based solutions, such as agroforestry. Restoring unproductive forest patches using agroforestry practices rebuilds carbon stocks and makes the landscape more resilient to climate events, while allowing cultivation areas to expand.

Shade-friendly crops cultivated within the foodscape, such as konjac and coffee, grow and thrive in the understory of taller trees. While agroforestry will not provide the biological richness of natural forest ecosystems, this nature-based approach can help effectively balance conservation, restoration, and economic goals. Such practices also help mitigate potential carbon emissions through less-intensive conversion.

To support land use planning adjustments, the East Kalimantan Provincial Government has worked in collaboration with a number of local authorities, NGOs, experts, and companies to create the Green Growth Compact. The goals of this group are to reduce deforestation by 80% by 2025 (and overall emissions) while growing the economy, and highlighting the importance of diverse representation and commitment within the members of the compact. In addition to conservation and agroforestry, the compact is linking its efforts to REDD+ to unlock more compelling incentives.

Planning for the future of the foodscape could help focus and enhance already ongoing efforts to evaluate, manage, and improve land use decisions. Looking at the members of the compact within the context of the foodscape could also help ensure it includes all stakeholders necessary to achieve environmental and economic goals in a way that sustains the East Kalimantan foodscape for years to come.

Landscape around Gorafe on the bank of the Gor River, Spain

Granada

Foodscape

Ensure climate resilience by promoting return to traditionally used practices

SPAIN

LOCATION: Andalusia, Spain
SIZE: 1.5 million ha

SYNOPSIS

For millennia, the varied terrain of southern Spain's Granada foodscape had primarily supported subsistence production. Extensive mountainous areas, with shallow soils, were cultivated with tree crops, including almonds and olives. When global markets began opening up in the 1980s, the highest-yielding agricultural areas transitioned from inherited traditional practices to highly mechanized systems intended to maximize production. Rainfed almond plantations and olive groves of the Granada foodscape, where production is constrained by the elements, had a harder time competing in global markets.

Now, less than half a century later, the mechanized approach has degraded soils, jeopardizing the long-term viability of regional olive production and compromising the profitability of almonds. More severe weather is also threatening the vulnerable yields of regional rainfed tree crops, for which economic margins are already narrow.

Protecting long-term production and profitability of crops within the Granada foodscape may require a large-scale shift

GRANADA

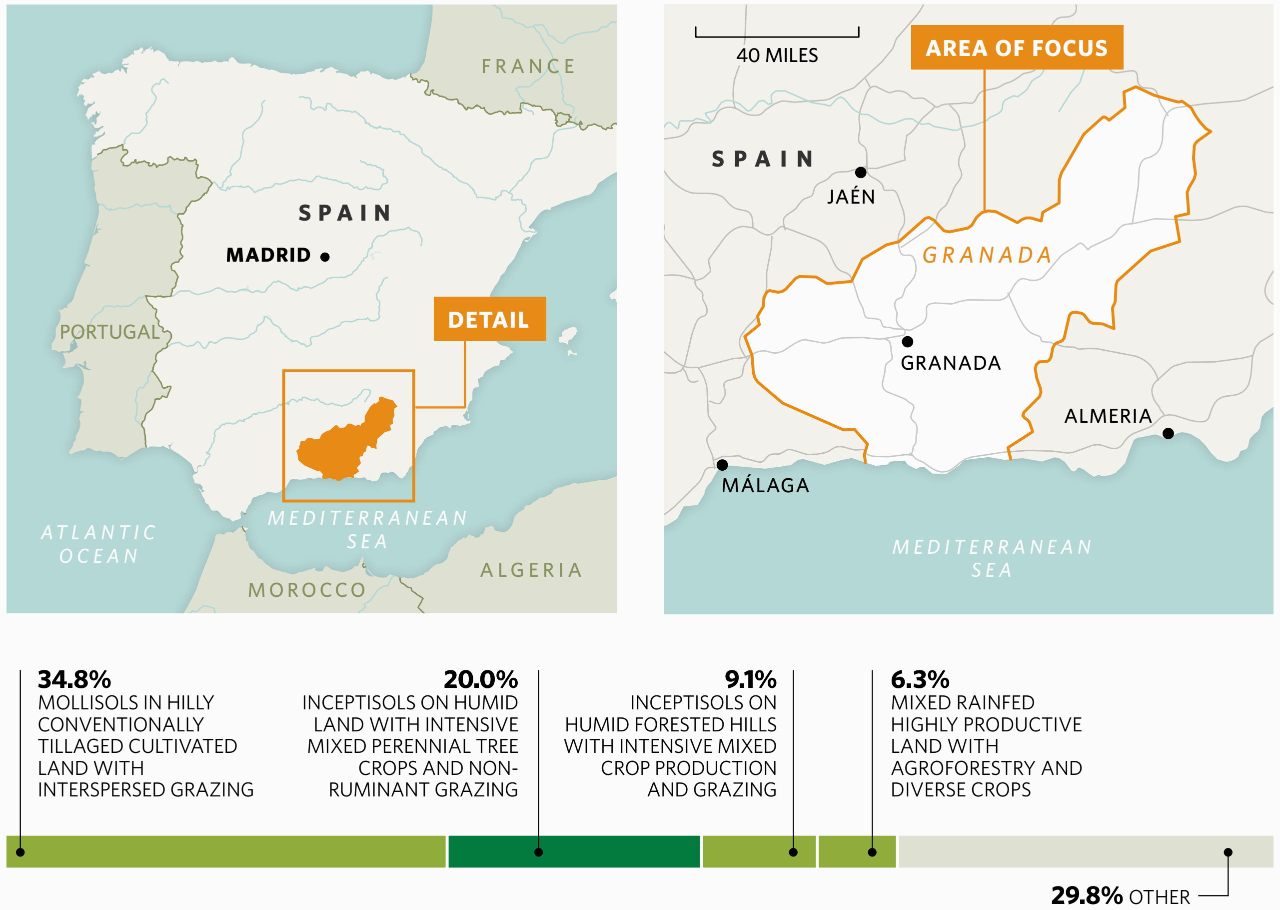


FIGURE 1. Map of Granada foodscape. The bars represent the most extensive foodscape classes within the foodscape. The color of bars indicates the intensity groups corresponding to those classes: intensive production dominant (dark green) and mixed mosaic food cultivation (light green). The other category includes the classes that each made up <5% of the foodscape area.

back to traditional practices. The need to adapt to increasing climatic irregularity makes change even more urgent. The legacy of traditional practices that are well suited to a climate-resilient future creates a promising path forward, bolstered by available public subsidies to mitigate the expense of transition across the foodscape. In the case of almonds grown in the Granada foodscape, one of the biggest factors pushing almond producers here to grow nuts organically is that they are not able to compete with the relatively cheap, irrigated almonds from the San Joaquin Valley (United States).

DESCRIPTION OF FOODSCAPE

Andalusia, the southern-most region in Spain, touches both the Atlantic and Mediterranean coastlines. The land surrounding the Atlantic river basins in the north is characterized by fertile soils and suitable for irrigation. Toward the southeast, both the mountainous terrain and more seasonally dependent Mediterranean-feeding rivers create challenging conditions for cultivation with limited water access. The patchwork of land use and land cover here, including urban centers, row crops, pasture, and tree crops, has been strongly shaped by the climate and water resources.

Olives growing on a tree, Granada, Spain

Spain's access to the European Economic Community beginning in 1985 marked a shift in the cultivation practices toward water efficiency, as growing industries such as tourism put greater strain on regional water supplies. The connection to larger markets also presented the potential for a globalized economy centered around Andalusia's growing agricultural commodity: olive oil. Where irrigation was installed, management practices were adjusted to accommodate machinery and the promise of higher productivity as a result.

> **Despite its long history of human occupation with densely populated and intensely cultivated pockets, Andalusia has protected terrestrial and marine areas that support migratory birds and emblematic vertebrates, such as the Iberian lynx, among many other species. The rich biodiversity native to the region is not, however, isolated from agricultural land use. In fact, 11% of Andalusia's agricultural land cover is part of the Natura 2000's European network of conservation areas, including 135,000 ha of olive groves, making the case for land sharing practices within groves.**

Granada, a province within southeast Andalusia and the focus of this foodscape, is dominated by mountainous terrain with a stretch of Mediterranean coastline (FIGURE 1). The northern part of Granada contains high-yielding olive groves supported by decades-old irrigation infrastructure. Along the coast, more abundant access to fresh water supports greenhouses and other horticultural crops important for Europe's winter produce supply.

The remainder of agriculture in the Granada foodscape is concentrated in lower rainfall areas with no irrigation, thus constraining productivity. The valleys are used primarily for cereal production while the inclined areas with poorer soils are cultivated with marginal olive groves and almond plantations. The areas in between support livestock and hunted wildlife.

CHALLENGES

Since adopting more globalized practices in the 1980s, both irrigated and rainfed agricultural systems in Granada are now approaching environmental and economic limits created by soil degradation and drought events.

Though the initial transition away from more traditional practices boosted yield and established the region as top producer of olive oil, the mechanized model is now damaging production. As water is the region's primary constraint, the soils between tree rows are often left bare (through a combination of tillage and herbicide application) to limit competition for water. Exposed soils, combined with steeper sloped terrain and the region's drier climate, cause average soil losses of 5.9 t/ha per year, and higher than 25 t/ha per year in some areas.

Erosion has been steadily degrading soils that were already shallow, placing the ultimate sustainability of the mechanized model of farming into question. For irrigated, high-production areas, this issue is jeopardizing the region's position in the global olive oil market, which would have implications for both the local economy and the region's cultural identity.

For rainfed olives, degradation is made more problematic by increasing rainfall extremes. During low rainfall periods, soils become drier with no alternative source of water. Come winter, the torrential rains heavily erode the tilled soils. These challenges are eating into the productivity of already low-yielding groves.

Though almonds are less water intensive, the water constraints on rainfed production are preventing almond farmers from competing with high-producing irrigated almond regions such as California's San Joaquin Valley foodscape. With anticipation of growing demand on water supply and greater climate irregularity, without a change in agricultural methods, such as a transition to organic agricultural practices that can command a higher price in the global market, almond producers in the Granada foodscape will continue to be strained to compete successfully against cheaper, irrigated crops in global markets.

BENEFITS AND VALUE OF NATURE-BASED SOLUTIONS IN THE GRANADA FOODSCAPE

The importance of agricultural exports to both culture and economy here has helped foster an appetite for regenerative solutions in the Granada foodscape. Sustaining this foodscape requires improved water management combined with an assisted transition back to some of the region's traditional practices. In general, traditional agricultural practices within the foodscape are centered around creating a more resilient water supply and anchoring soils to minimize erosion. Many of these solutions have always been based in the benefits nature provides to agriculture.

Planting cover crops in exposed soils between tree crop rows protects soil from erosion, helps accumulate soil organic carbon, and, over time, improves soil structure. In addition to between-row cover, planting native hedges around field edges helps capture soil, improves water infiltration into soil, and provides habitat for diverse native species, especially birds. Swales dug into field boundaries contribute to the resilience of water resources by collecting excess rainwater to buffer times of water scarcity.

Though these more traditional practices tend to generate marginal net economic gains for irrigated and rainfed olive growers (Supplementary Material, Archetype A and Archetype B, respectively),[1] the potential reduction in soil loss is a significant benefit. In addition, cover crops and hedges give farmers the opportunity to rent fields out for hunting and grazing for supplementary income. Integrating livestock, preferably sheep or horses, would require careful management to protect tree crops. However, additional income from these uses of marginal groves, in particular, could help buffer farmers' income from highly variable rainfall-dependent yields.

Realizing this regenerative transition for rainfed almond plantations (Supplementary Material,[1] Archetype C) in the Granada foodscape requires strategic public sector support to help farmers link soil health and water management improvements to lucrative market access.

For example, given the known resource constraints limiting almond production, the regional government is bolstering subsidies to help capture the organic market for almond exports. The subsidies help farmers through the transition to organic production and continue to give them a bump beyond conventional almond subsidies once they are certified.

Groves of tree crops near the town of Alhama de Granada, Granada, Spain
© Ken Welsh/UIG/Gettty images

Ripe oranges, Granada, Spain.

Though implementation costs are higher compared to olive groves (Supplementary Material,[1] Granada – Archetypes A and B), incorporating organic certification into the regenerative transition for almond plantations provides a net gain of $44,000 annually for a 35 ha plantation. Access to premium pricing in organic markets drives the drastic change in profit. Adopting nature-based regenerative solutions is a small step for farmers on the path to organic certification, with costs mitigated by the substantial subsidies.

However, public-private schemes are not the only enabling factors for a successful transition to a nature-based regenerative agricultural future in the Granada foodscape. The globalization of practices within the Granada foodscape are recent enough that there is still a strong cultural memory of generational farming. Fortunately, regenerative solutions build on traditional practices handed down through generations, so adoption by producers within the Granada foodscape may be met with less resistance compared to untested practices.

Scaling such nature-based regenerative practices across a total of 300,000 ha within the Granada foodscape could bring as much as $128 million per year in additional revenue (FIGURE 2). Coupling modernized water management infrastructure with traditional regional practices could set this foodscape on a path to regenerating their soils while sustaining and improving their extensive tree plant economy.

AGGREGATION OF ARCHETYPES TO THE FOODSCAPE LEVEL

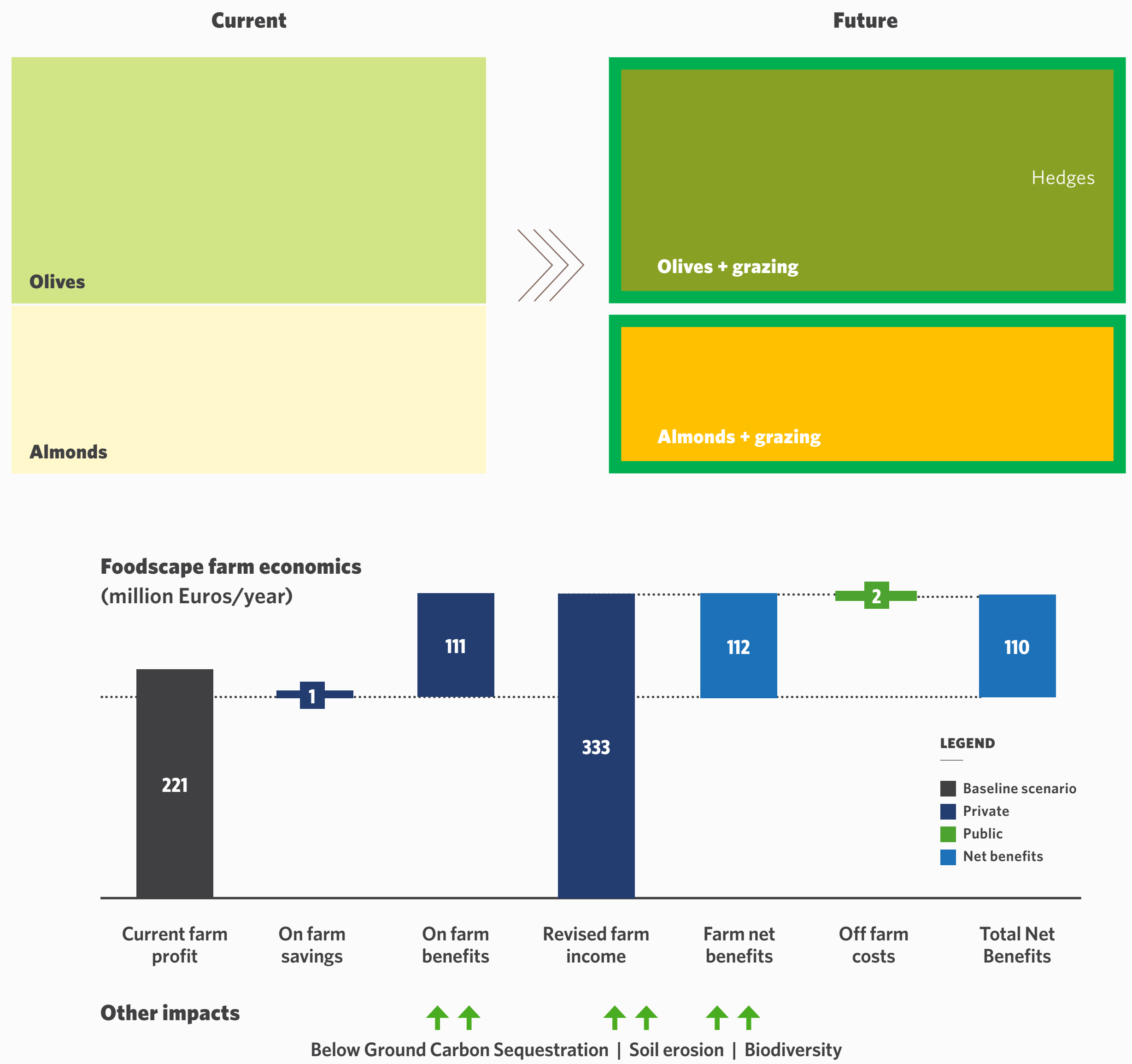


FIGURE 2. Summary of economic analysis of nature-based solutions in the Granada foodscape. **Disaggregated costs & benefits toward $[110 million Euro conversion] million net benefits from several farm archetypes:** Starting with baseline current farm profits (grey, far left), the diagram shows proposed future on farm benefits and costs (dark blue), totaling farm net benefits of [112 million Euro conversion] (light blue, middle). Additional public off farm benefits and costs (light green) added to and subtracted from farm net benefits equals [110 million Euro conversion] total net benefits (light blue, far right). Other impacts are qualitative assessments of other ecosystem service benefits. The proposed nature-based solutions associated with the farm archetypes are represented in the boxes. See Supplementary Material for a description of methods.[1]

Livestock roam near the Great Mosque of Djenné, Mopti, Mali
© Poncho/Getty Images

Mopti
Foodscape

Governance systems to manage land use conflicts and enable nature-based solutions

MALI

LOCATION: Inner Niger Delta, Mali
AREA: 8 million hectares

SUMMARY

The Mopti foodscape in Mali is a mixed-used landscape that supports pastoralism, rainfed cereal production, fish harvesting, and irrigated rice based on the annual rising and falling of the Inner Niger River Delta. Since 2011, ongoing and increased violent conflict in Mali has exacerbated the weakening of traditional methods for governing these multiple land uses.

Combined with environmental changes to the Inner Niger Delta, this weakening of institutions and long-standing traditions has caused, and is the result of, conflicts among ethnic groups associated with different land uses, specifically Fulani pastoralists and Dogon cereal farmers.

Short-term conflict management is essential, but to manage the Mopti foodscape for sustained and sustainable productivity, viable methods of land use governance to manage tensions must be reestablished. Planning and working at the foodscape level could help provide a flexible framework for identifying shared values and complementarities among different land uses and land users.

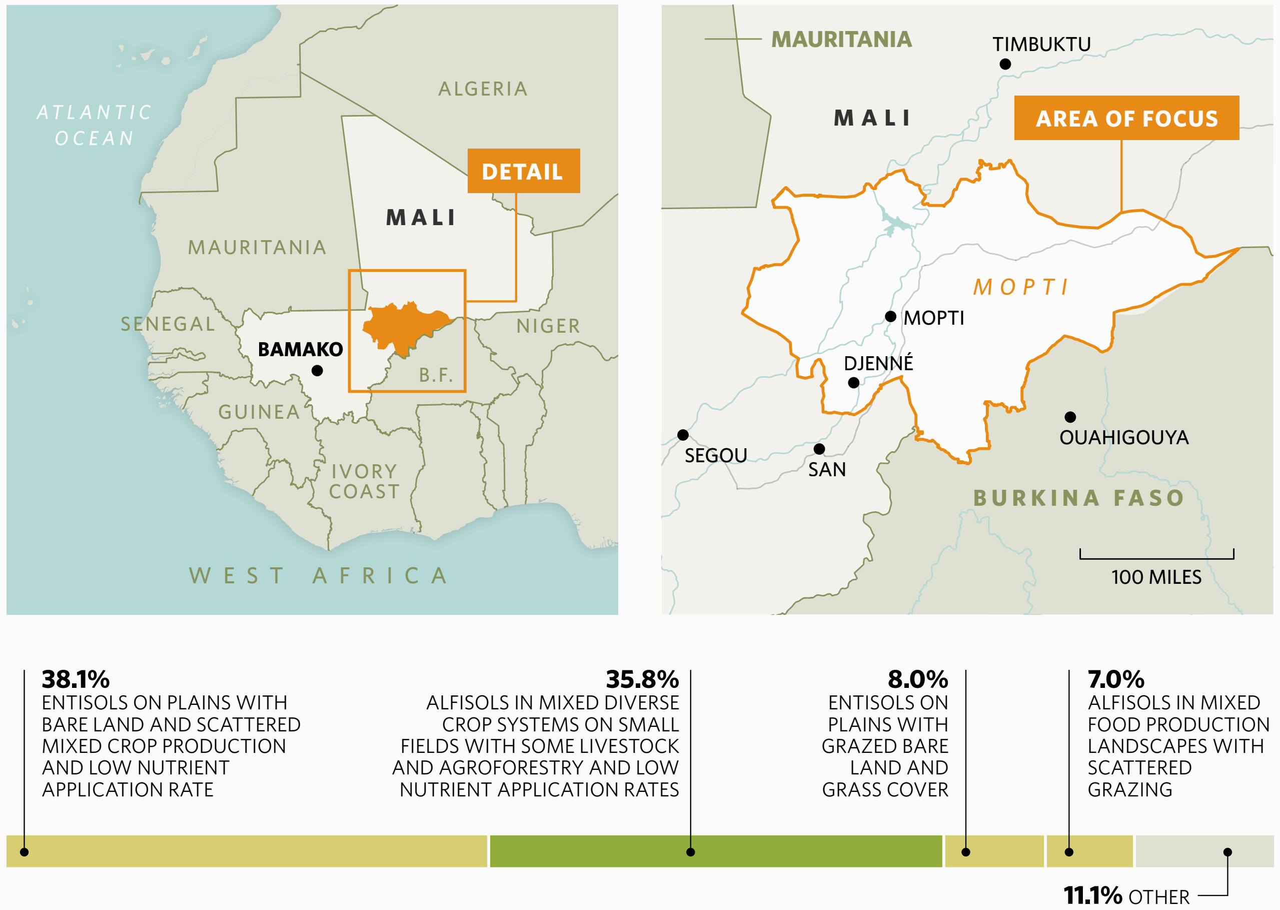


FIGURE 1. Map of Mopti foodscape. The bars represent the most extensive foodscape classes within the foodscape. The color of bars indicates the intensity groups corresponding to those classes: scattered cropland and grazing (yellow) and mixed mosaic food cultivation (light green). The other category includes the classes that each made up <5% of the foodscape area.

Equitable, stable governance within the foodscape is an essential precondition to scaling traditional and newer nature-based solutions, such as farmer-managed natural regeneration, that offer an opportunity to produce crops and livestock in ways that are both resilient to climate shocks and can lessen tensions among different land uses. Ultimately, scaling any solutions, including those based on nature, will require flexible tenure systems that incentivize exclusivity rights for farmers and seasonal access rights for pastoralists.

DESCRIPTION OF FOODSCAPE

The Mopti foodscape (FIGURE 1) depends on the seasonal flooding and retreat of the Inner Niger Delta – the second-largest wetland in Africa after Botswana's Okavango Basin. In the dry season, when the river is lowest, ethnic Fulani herders graze cattle on grasses that grow in the deeper waters, and Mandé and Dogon farmers cultivate rice in flooded areas. Bozo fishers also collect fish that have been stranded in dry areas after the river water has receded.

The term Mopti, which is a political region of Mali, comes from the Fulani word for "coming together," which conveys a sense of the plurality of production systems in this area, all affected by and dependent on the river.

When the river floods in the rainy season, the pastoralist Fulani move their livestock to plains elsewhere within the foodscape where they use pasture resources. This transhumance (moving livestock from one grazing ground to another in a seasonal cycle) has been the foundation of the Fulani livelihood for centuries. It has also benefitted farmers; when the livestock move, they leave behind well-fertilized areas that can be used for rice production. Farmers in the Inner Delta area grow mainly rice, while farmers in the drier plains grow rainfed crops such as millet, sorghum, groundnut, cowpea, and sesame.

The Inner Delta supports more than 67,000 ha of irrigated rice, Mali's main cereal, mostly through dams that have been established along the river.[35] The river also supports an annual fishing harvest of 130,000 tons.[35] In the rainy season, Bozo fishers catch fish with nets in the flooded river areas. In addition to supporting diverse food livelihoods, the Inner Niger Delta is a unique and important ecological habitat.

The third largest Ramsar site in the world, the Inner Niger Delta is a bright spot of green in an otherwise arid landscape. As such, it is crucial habitat for both endemic and migratory species. Every year, more than 1 million birds of more than 350 species use the delta. Important species include manatees, hippopotamus, and nearly 150 species of fish, of which 25 are endemic.[35]

The area is also an important cultural and historical center. While the universities and libraries of Timbuktu are relatively well known, major towns in the Inner Niger Delta (Youvarou, Tenekou) have libraries and learning centers dating back to the Middle Ages. The complex ecological and socio-occupational systems required sophisticated, adaptable, and democratic governance systems.

Bozo fisherman on the Niger River, Mali
© Reynald Schmid/Getty Images

A field of onions in the village of Doura, Segou, Mali

For centuries, management of the region's resources was enabled by customary land use agreements. In Mopti, the Fulani were considered to have historical land use rights and thus held the role of political elites. The colonial and postcolonial era strongly affected power dynamics and resulting land use. The colonial and postcolonial period favored policies aimed at agricultural development and shifted emphasis away from pastoralism.

Between 2000 and 2010, the livestock sector in Mali received less than 8% of the spending on agriculture sector, despite contributing one-third of the country's agricultural GDP.[36] At the same time, technological innovations in agriculture, such as mechanization, have enabled expansion of cultivated area, up to the tripling of field sizes, thus exacerbating conflict with pastoralists.

CHALLENGES

One of the key environmental changes affecting the Mopti foodscape, as well as other parts of Mali, is the extreme decrease – by 50% since the 1980s – in the amount of water flowing into the Inner Niger Delta. The causes for such a large decrease in water flow include declines in upstream rainfall as well as changes to natural waterflows associated with human uses, especially upstream dams and irrigation.

Consequently, the dwindling water flows have led to an associated decrease in the deeper-water areas where hippo grass (*Echinocloa stagnina*) – known locally as *bourgou* – has historically grown. Bourgou is an important food resource for grazers' livestock as well as other wildlife. A further complicating factor within the Mopti foodscape is that the loss of these deeper water areas has created opportunities for farmers to expand irrigated rice into traditionally *bourgou* areas.

One of the major social changes in the region is an increase in armed conflict since 2015. The Arab Spring led to a surge of arms and influx of armed groups into Mali from Libya, which exacerbated historical tensions leading to a coup in 2011. Insurgent groups spread and were active in Mopti by 2015. In this context, perennial land use disagreements began to escalate into violent conflict driven by the expansion of cultivated land into grazing reserves, animal movement corridors, and areas around wells. Such conflicts have led to many hardships in the Mopti foodscape, including human displacement and food insecurity.

Increased violence has also changed the way conflicts are now mediated within the foodscape. Instead of heads of community having the authority to mediate and resolve disputes, that power has now shifted to armed militias. This change of long-standing local and cultural norms further erodes the customary institutions that historically adjudicated land use disagreements and governed land and natural resources, especially those involving common property, within the Mopti foodscape.

For pastoralists, agriculture expansion may be a threat; for farmers, it represents a positive change. In the Mopti foodscape, both cropland expansion and contraction have occurred, but for different reasons. Expansion is a longer-term change due to public policy priorities, shifts in cultural power, and technical developments.

Despite increased climate variability, cereal production in the Mopti foodscape rose from around 400,000 tons in the early 2000s to 1.22 million tons by 2015, which is partially attributable to a 30% increase in cultivated area. More recently, cropland has contracted due to the threats of violence, mainly from extremist groups. Because people do not want to travel far from their communities, cropland area has decreased by 25%.[37]

BENEFITS AND VALUE OF NATURE-BASED SOLUTIONS IN THE MOPTI FOODSCAPE

Of foremost importance is immediate conflict management and de-escalation of armed tension among communities in the Mopti foodscape. Without this, long-term improvements to land use cannot be developed. There have been attempts at peace agreements brokered by the central government of Mali between the Fulani and Dogon, the most recent of which was signed in January 2021. However, a coup in May 2021 calls into question the role and effectiveness of the central government in lasting conflict resolution. Ultimately, the people of Mali and those of the Mopti foodscape require trusted mechanisms for resolving the underlying tensions among communities over land use.

Fortunately, within recent history there are long-standing examples of cooperative, mutually beneficial shared land use between pastoralists and farmers. For example, the annual Diafarabé crossing of thousands of livestock from upland pasture back to the Delta is an example of the success of traditional institutions and land uses. The crossing was not set on a fixed day but depended on when farmers south of the river had harvested, so herds could come across without damaging crops. Planning within the foodscape level here could offer avenues for creating new flexible and nature-based solutions that are sensitive to the needs both of farmers and pastoralists.

Crop fields mixed with parkland at the foot of the Bandiagara Escarpment, Mopti, Mali
© Timothy Allen/Getty Images

For farmers, exclusive and private tenure security is a priority to incentivize investments in plots of land. Yet pastoralists require flexible systems so that livestock can access these lands at optimal times. Developing trusted, equitable, and effective processes for negotiation and conflict resolution are therefore more important than fixed inflexible or one-size-fits-all policies around tenure laws.

As the land uses in the Mopti foodscape shift in response to climate change, cultural shifts, and a pronounced decline in water flow, farmers and pastoralists increasingly seek more diverse forms of food production and sources of revenue. Because of declines in fish stocks in the Niger River, there is growing emphasis on stocking fish farms, which now account for around 10% of fish production in the Inner Niger Delta. Fish farming uses seasonal ponds as well as soil pits where soil has been excavated for other uses, such as brick making. With the emphasis on fish farms, there is also growing interest in fish processing techniques that capture more value, such as fish smoking practices that extend food storage life with less fuel wood. These fish are sold in local markets and dried and exported throughout the broader region.

The management of native trees, also referred to as farmer-managed natural regeneration (FMNR), is a nature-based solution used across the Mopti foodscape for centuries. Specifically, FMNR involves managing native species through coppicing naturally establishing trees and shrubs or allowing the dormant seed and root bank to germinate. Species can be selected for specific land-management purposes, such as *Faidherbia albida*, a fast-growing deciduous tree, that has long been used for reducing erosion, improving soil fertility, and providing animal fodder and fuelwood. Other species, including *Zizyphus mauritania* and *Parkia biglobosa*, provide non-timber products like fruits and cooking ingredients.

FMNR is a nature-based solution for farmland management that also provides alternate revenue streams for farmers and more climate-resilient production that could lead to lower pressure on natural resources. The potential for growing fodder alongside other benefits may create opportunities for this solution to contribute to cross-sectoral land use planning within the Mopti foodscape. Successful FMNR requires tree and land tenure as well as collective action to minimize mortality of regenerating trees. Cultural shifts in the region, wherein Fulani become more sedentary and Dogon take on more livestock, potentially make this type of mixed land use approach more viable.

Truck hauling recently harvested rice to market, Ludhiana, India
© TNC India

Punjab-Haryana Foodscape

Target incentives to jointly improve crop production, water security and human health

INDIA

LOCATION: Northwest India
AREA: 9.5 million hectares

SYNOPSIS

The Punjab-Haryana foodscape in India is an intensively cultivated breadbasket where Green Revolution innovations in crop breeding led to high-input, high-yielding rice-wheat agriculture. That crop combination, in addition to government provision of free electricity to rural areas, drove high rates of groundwater pumping and overdraft.

Subsequent policy to limit dry-season irrigation led to a narrower window between rice harvest and wheat planting, which inadvertently contributed to large-scale crop residue burning as a way to quickly prepare fields for wheat.

At peak burning periods, agriculture burning contributes around 30% of fine particulate matter in New Delhi, the capital, where it causes respiratory harm, contributes to climate change, and disproportionately affects the poor who are less able to take adaptive measures. Technical solutions have been developed to enable seeding wheat without burning rice residue, but these technologies have not been adopted as widely as necessary despite public investment.

The Punjab-Haryana foodscape demonstrates the potential pitfalls of narrowly focused policies that can lead to unintended consequences. Policies aimed at limiting water depletion ultimately created another problem: poor air quality in New Delhi. Lasting solutions to both water depletion and poor air quality here require combined and complementary approaches, including nature-based solutions for managing farms without the need for burning.

Adoption of nature-based and other relevant solutions can be accelerated by providing a clear context for aligning public policy and economic incentives around multiple outcomes, including crop production, air quality, and water security.

ABOUT THE FOODSCAPE

The Punjab-Haryana foodscape is an important breadbasket for India. The majority of this landscape is cultivated; 84% of Punjab is cropland compared to a national average of 40%. In most of the foodscape, irrigated rice and wheat are grown back-to-back.

PUNJAB-HARYANA

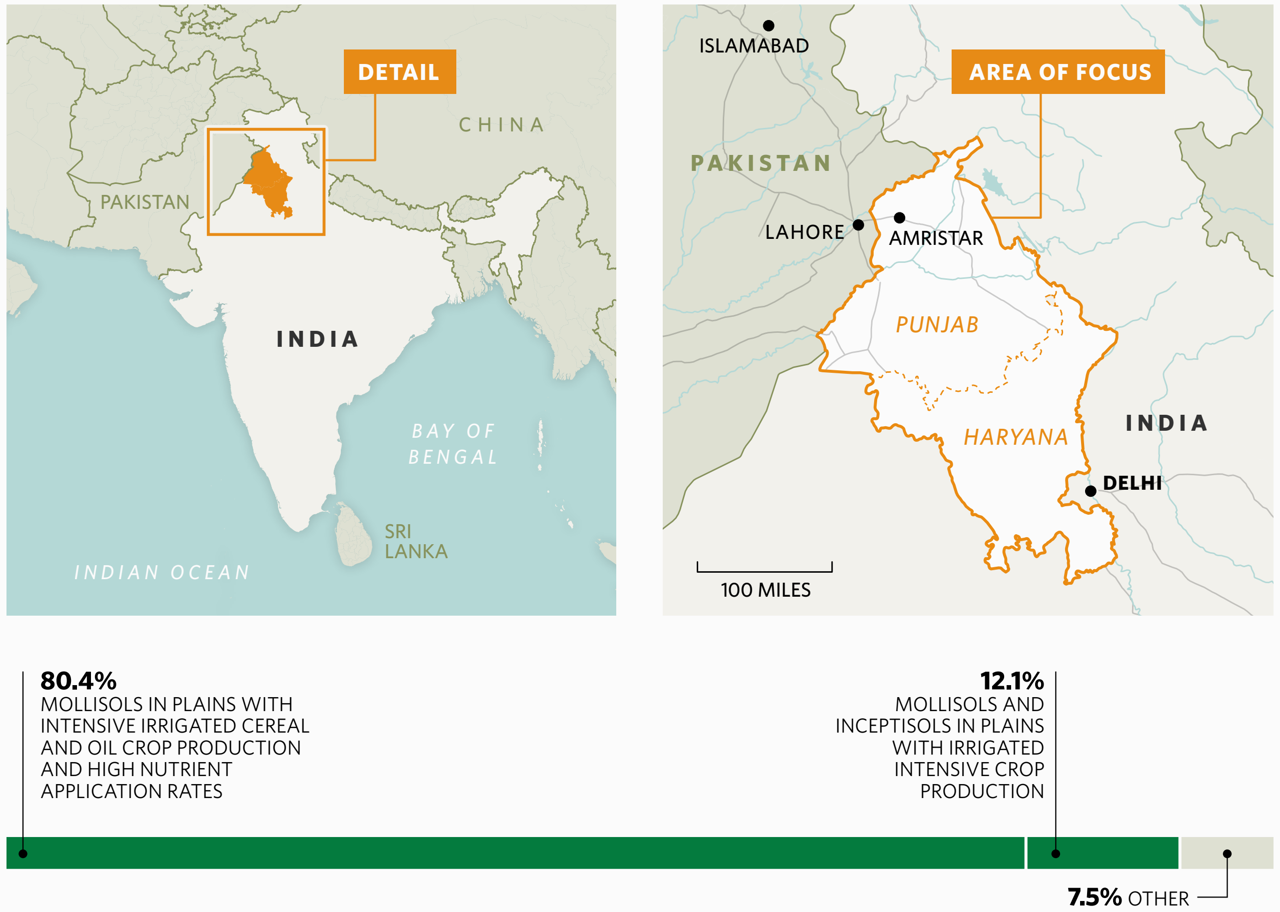


FIGURE 1. Map of Punjab-Haryana foodscape. The bars represent the most extensive foodscape classes within the foodscape. The color of bars indicates the intensity groups corresponding to those classes: intensive production dominant (dark green). The other category includes the classes that each made up <5% of the foodscape area.

Crop Residue Management TNC India / truck hauling recently harvested rice to market, Ludhiana, India
© TNC India

In the past, there was a greater diversity of crops and traditional crop varieties that were well suited to environmental and soil conditions. Crops that have declined in the area include maize, pearl millet, sorghum, lentils, peas, sugarcane, peanut, mung bean, barley, rapeseed, mustard, and sunflower. Part of the reason for this decline has been demand from the Food Corporation of India, India's national food distribution system, which targets high-yielding paddy rice varieties to provide affordable staples throughout India. Some farms produce a higher quality basmati rice for local consumers able to afford a higher-end product and for international export.

CHALLENGES

The Punjab-Haryana foodscape faces severe groundwater shortages. Federal policy that provides free electricity to rural areas enabled widespread pumping of groundwater to irrigate rice and wheat in semi-arid zones. Because both water and electricity are free to farmers, there is little economic incentive to limit water extraction. Yet groundwater in this region is declining by over 70 cm per year.[38]

State governments responded to groundwater depletion by enacting policies to limit water use. The states of Punjab and Haryana adopted a Preservation of Subsoil Water Act in 2009. In the Punjab, the act's approach to conserving groundwater was to mandate delayed planting of rice to correspond with the onset of the monsoon season. During the monsoon evapotranspiration of water from crops is lower and less irrigation is required.

Rice is harvested, and soon thereafter wheat is planted. Farmers who plant rice to coincide with monsoon rains have only 10–20 days to get wheat planted. This narrower window created a need for quick approaches to crop residue management, which led to a sharp increase in crop residue burning. Approximately 60% of the crop residue from high-yielding rice purchased by the Food Corporation of India is burned. Basmati rice fields are not often burned, however, because basmati is harvested manually and its straw can be used for fodder, which means it is cut lower to the ground during the harvesting process.

The period of crop residue burning overlaps with seasonal winds that carry the particulate matter from the Punjab-Haryana foodscape to New Delhi where it then contributes 30% of the total amount of fine particulate matter shrouding the city during the burning season.[39] During peak air pollution periods, particulate matter levels in New Delhi can be more than 10 times India's National Ambient Air Quality Standard. The government of the greater New Delhi area has taken policy measures to address short-term spikes, such as closing schools and high-polluting industries during peak emissions periods.

Ability to adapt to emissions is not equal among households. Wealthier households increasingly leave the city during peak periods and purchase air purifiers or respirators. Individuals who work outdoors or who cannot afford filters or leaving the city therefore experience the greatest impact of air pollution. One immediate opportunity to reduce burning is technology and equipment that allows for direct seeding of wheat into rice stubble (the Happy Seeder). The federal government provided $240 million in subsidies for these crop-residue management technologies. Because cooperatives, rather than single farmers, receive a higher subsidy rate, the subsidies create an opportunity for entrepreneurs to develop service provider models where they enable use of these tools at a fee per area. Unfortunately, demand has been low with some machines operating at only 20% of capacity. Part of the reason for low demand is that it requires farmers to make changes to irrigation and nutrient management practices. It also conflicts with cultural preference for seeding into a clean field.

BENEFITS AND VALUE OF NATURE-BASED SOLUTIONS IN THE PUNJAB-HARYANA FOODSCAPE

In addition to aligning incentives around the use of technologies such as the Happy Seeder, another opportunity to reduce burning is to incentivize crop diversification away from the high-yielding rice varieties that contribute the most to burning (FIGURE 2). In addition to lowering burning, more diverse crops can decrease irrigation needs and increase nutritional diversity.[40]

The simplest crop diversification strategy is to convert a portion of high-yielding rice to basmati rice. This crop change can be combined with other agronomic practices that reduce water use, such as direct seeding of rice and composting of crop residue. Together, these actions could increase farm net revenue by around $1,000 per year, though initial costs of transition would be about one-third of current farm revenue and therefore require new sources of capital or redirection of current subsidies and investments (Supplementary Material, Archetype A).[1]

Because assured income through rice-wheat procurement systems creates such a strong economic signal for the continued production of high-yielding rice, a shift in governmental cereal procurement policies would be the first step toward incentivizing crop diversification. Going further, policies could jointly target crop production, water availability, and human health (air quality). Overall, short-term solutions – such as switching to basmati rice – could produce more than $900 million in net benefits per year over the whole foodscape. Off-farm benefits would be more than $700 million (FIGURE 2).

Over the longer term, there can be further diversification to crops that were traditionally grown in the region – pulses, legumes, other cereals – and perennials. This could provide similar revenue increases to basmati rice, and many of these other crops are also well adapted to drought stress. The addition of perennial woody vegetation would also increase carbon storage.

AGGREGATION OF ARCHETYPES TO THE FOODSCAPE LEVEL

FIGURE 2. Summary of economic analyses for the Punjab-Haryana foodscape. **Disaggregated costs & benefits toward $1210 million net benefits from several farm archetypes:** Starting with baseline current farm profits (grey, far left), the diagram shows proposed future on farm benefits and costs (dark blue), totaling farm net benefits of $US 965 million (light blue, middle). Additional public off farm benefits and costs (light green) added to and subtracted from farm net benefits equ659als $US 1210 million total net benefits (light blue, far right). Other impacts are qualitative assessments of other ecosystem service benefits, except for water savings which was quantified. See Supplementary Material for a description of methods.[1]

Aerial view of farmland, San Joaquin Valley, CA, USA
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San Joaquin Valley Foodscape

Balance food production and biodiversity under water scarcity

UNITED STATES

LOCATION: California, United States
AREA: 13 million hectares

SUMMARY
At the beginning of the 20th century, California's San Joaquin Valley was a dry plains habitat. This seems incongruous with the current, public view of the valley: intensive agriculture and one of the world's most important breadbaskets for fruits, vegetables, and tree crops. This contrast captures the fundamental transformation of the San Joaquin Valley foodscape: a once arid landscape that now has 2 million ha of irrigated cropland and exceeds sustainable water use by more than a half-trillion gallons of water per year.

To address this imbalance, California passed the Sustainable Groundwater Management Act (SGMA) that requires the San Joaquin Valley to come into hydrological balance over the next several decades. Achieving this balance will likely require fallowing around 250,000 ha of agricultural land. At the same time, the San Joaquin Valley foodscape needs to maintain its agricultural productivity.

THE SAN JOAQUIN VALLEY

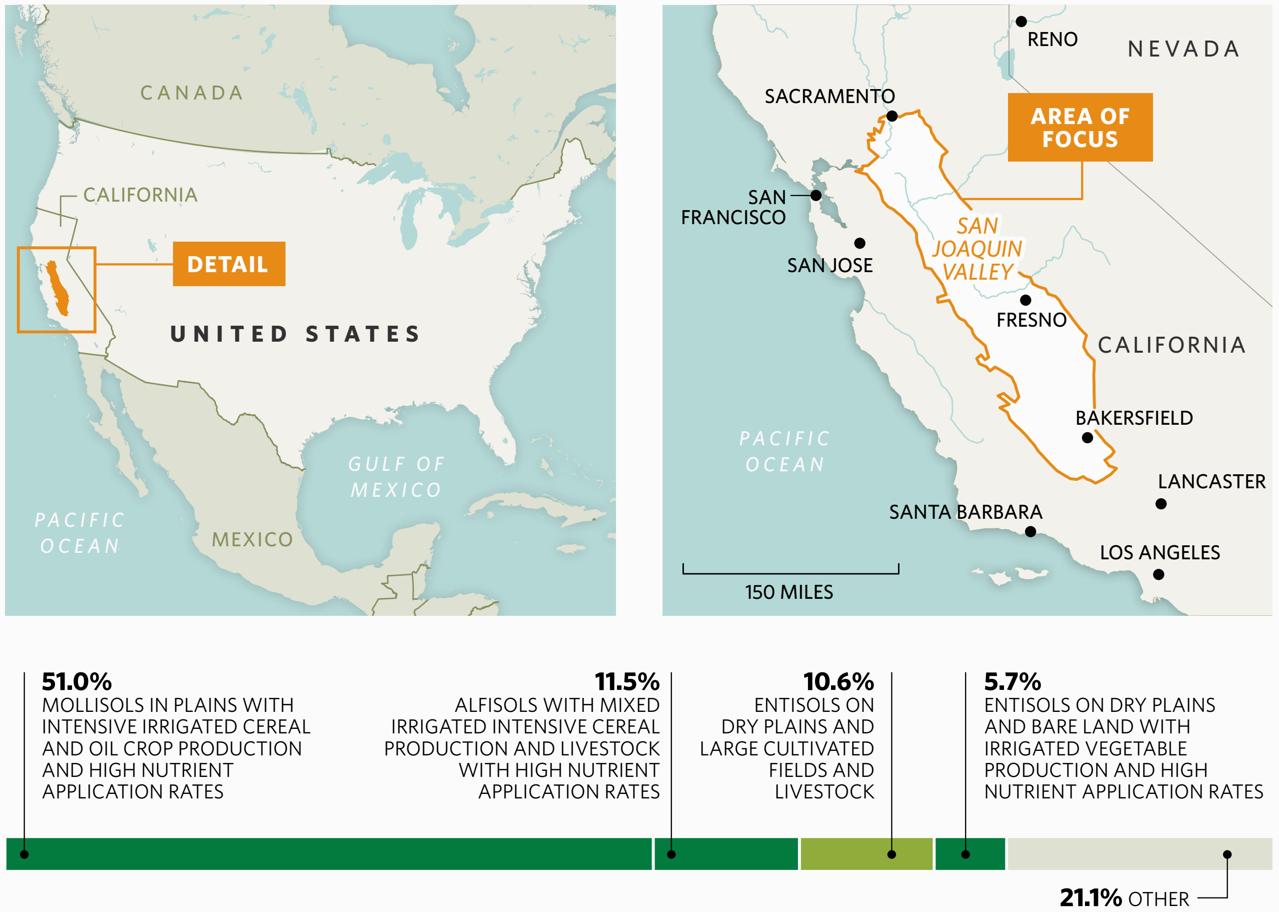

FIGURE 1. Map of San Joaquin Valley foodscape. The bars represent the most extensive foodscape classes within the foodscape. The color of bars indicates the intensity groups corresponding to those classes: intensive production dominant (dark green) and mixed mosaic food cultivation (light green). The other category includes the classes that each made up <5% of the foodscape area.

In this time of transition for the San Joaquin Valley and its communities, planning at the level of the entire foodscape could help show where nature-based solutions, such as restoration of retired agricultural lands, would be most useful in reducing the impacts of climate change and policies like SGMA on farmers and keep them farming. Transitioning to a more diversified landscape that balances biodiversity, agriculture, water stewardship, and energy production will require careful management to ensure that the most vulnerable groups (e.g., disadvantaged communities and small family farms) do not carry a disproportionate amount of the costs of transition.

Nature-based solutions here, especially strategic restoration, could help recover biodiversity and benefit local communities through sustainable agriculture, improved water supply, water quality, air quality, and access to open space.

Almond trees reflected in flooded irrigation water in the San Joaquin Valley, California, USA
© David Gomez /Getty Image

DESCRIPTION OF FOODSCAPE

The San Joaquin Valley foodscape (FIGURE 1, p.10) contains 2 million ha of irrigated agricultural land. Farms in the region range from small family farms under 5 hectares to large agricultural operations with hundreds to tens of thousands of hectares in production. This foodscape produces one-quarter of the fruits, nuts, and vegetables consumed in the United States and is home to six of the top 10 dairy-producing counties in the United States.

Seven of California's top food-producing counties are in the San Joaquin Valley foodscape and produced more than $30 billion of agricultural revenue in 2016, which has increased more than 70% since the 1980s.[10] This increase in revenue largely reflects expansion of high-revenue commodities including milk, almonds, grapes, citrus, cattle, and pistachios. From 2000–2016, the area of perennials grew by 27%.[41] Irrigated horticultural crops, though making up a smaller area, still represent a crucial element in national and global supply chains. For instance, 95% of the processing tomatoes in the United States come from California, and the San Joaquin Valley foodscape makes up 70% of the state's production.[42] The majority of California's grapes — both for wine and table grapes — are grown in this area. This level of production has been allowed by unsustainable levels of surface and groundwater use.

Some of that water comes from the surface water sources within the San Joaquin Valley — rivers fed by winter rains and snowmelt from the Sierra Nevada Mountains. The region also imports surface water from the Sacramento River Valley via the Sacramento-San Joaquin Delta and a series of large canals on the eastern and western sides of the valley. Yet many farmers rely on pumping groundwater, especially in drought years when surface water deliveries are lower. Paired with agricultural expansion, this intensive use of groundwater has led to overdraft of aquifers (see next section on Challenges), widespread subsidence, and impacts to drinking water access in some communities.

Originally inhabited by the Yokut and Miwok people, the vast, flat valley floor of the San Joaquin Valley was historically composed of hundreds of thousands of hectares of permanent and seasonal wetlands, including the great Tulare Lake. These wetlands formed the backbone of the Pacific Flyway that supported millions of migratory shorebirds and waterfowl on their journeys to and from their breeding grounds. Surrounding the wetlands was an upland desert scrub ecosystem that was home to dozens of species found nowhere else on earth. From 1850–1950, these wetlands were drained and the landscape was transformed from one that supported limited dryland cropping and rangelands to intensive, irrigated fruit and vegetable crop production.

Rebalancing land and water use in the San Joaquin Valley foodscape to achieve groundwater sustainability presents an opportunity to achieve long-term water security for the region's farms while also recovering its native species, many of which are still present in small pockets of protected areas, by restoring their native habitat on working and retired agricultural lands.

Over time, 95% of the original habitats of the San Joaquin Valley, from permanent and seasonal wetlands to upland desert scrub, were converted, primarily to agriculture. As a result, many of the unique San Joaquin desert species, including the giant kangaroo rat, blunt-nosed leopard lizard, Tipton's kangaroo rat, Bakersfield cactus, San Joaquin woolly-threads, and the San Joaquin kit fox, are now listed as threatened or endangered, and the wetlands that millions of migratory birds rely on have been largely lost.

Almond (Prunus dulcis) orchard trees reflected in flooded irrigation water used in watering the trees.Taken in the San Joaquin Valley, California, USA.

CHALLENGES

Over time, the agricultural footprint of the San Joaquin Valley has continued to grow, expanding by more than 800,000 ha from the end of World War II up to the turn of the millennium. Due to this large-scale transformation of the landscape and the high level of endemism of the species that relied on the valley's desert scrub habitat, the San Joaquin Valley has some of the highest concentrations of endangered species in the United States.

At least 30,000 ha of upland habitat would need to be restored and/or protected to support the recovery and potential delisting of the 11 most important threatened species within the San Joaquin Valley.[43]

For a dryland ecosystem to achieve the status of one of the most important food-producing regions in the world requires large-scale transformation of water resources for irrigation. For most parts of the valley, groundwater accounts for about 40% of irrigation water in wet years and up to 60% in dry years, with the remainder supplied by imports from the Sacramento River and major tributaries of the San Joaquin River and Tulare Lake watersheds that flow out of the Sierra Nevada Mountains.

However, approximately 20% (>300,000 ha) of all irrigated lands in the San Joaquin Valley are completely dependent on groundwater for irrigation. Changing water supplies due to drought, climate change, and water policy have resulted in an overdependence on groundwater. The San Joaquin Valley has an overdraft of water of approximately 0.7 trillion gallons per year.[41]

The overuse of groundwater has many consequences that go beyond availability of water for irrigation. Overdraft is leading to rural drinking water wells drying up, decreased water levels in rivers and wetlands, and land subsidence, which has exceeded 25 feet in some areas of the San Joaquin Valley and which can lead to the collapse of infrastructure such as the canals that transport water throughout the valley.

Dependence on groundwater pumping has been exacerbated by crop shifts from annual crops that can be fallowed in dry years toward perennial crops, such as almonds, that require irrigation even when water is most scarce. Because these crops represent long-term investments, and because they need to be irrigated every year to stay alive, there is little flexibility to downscale irrigation in drought years, resulting in a "hardening" of water use.

The pressures that led to groundwater overdraft in the region are likely to intensify as climate projections predict that the whole San Joaquin Valley will be in a desert climate in the next 50 years. Increasing soil salinity is also a major challenge for agricultural production in the San Joaquin Valley. Increased salinity occurs when groundwater pumping draws up soluble minerals and they accumulate in the root zone. It has been estimated that soil salinity costs farmers in the San Joaquin Valley $370 million per year.[44]

The San Joaquin Valley is a hotspot for poor water and air quality, including some counties designated by the U.S. Environmental Protection Agency as having air quality hazardous to human health.[45] More than half of the children living in the valley suffer from asthma. Air quality problems are due to the combustion of fossil fuels associated with tractor use, shipping trucks, and nitrogenous fertilizers.

Because rural areas depend largely on groundwater sources for drinking water, they are disproportionately exposed to agricultural and naturally occurring pollutants such as nitrates and arsenic. Excess nitrates in drinking water, which leach into groundwater from overapplication of agricultural fertilizers, cause birth defects. In addition to nitrates, certain areas of the San Joaquin Valley – and in particular deeper groundwater – have naturally higher arsenic levels, which is linked to heart disease, diabetes, and cancer.

SOLUTIONS

In 2014, spurred by increasing overdraft in the midst of a historic drought, California passed its first attempt at groundwater regulation, the Sustainable Groundwater Management Act (SGMA). SGMA (pronounced Sigma) mandated the creation of new groundwater sustainability agencies that are now responsible for developing Groundwater Sustainability Plans to bring each of their jurisdictions into balance by 2040. The geographical boundaries of these agencies were defined by local stakeholders and do not necessarily map onto traditional hydrological boundaries. The agencies aim to achieve groundwater sustainability through a combination of water supply enhancement projects – new imports and groundwater recharge – and demand reduction, such as irrigation efficiency projects, crop switching, and fallowing of marginal cropland. Adoption of practices like local or regional water trading

Almond orchard with ripening fruit on trees and fame worker mowing grasses between trees.
© David Gomez /Getty Images

could aid in optimizing allocation of water supplies to where they are most needed, requiring less demand reduction to achieve sustainability.

For instance, water trading restricted to local basin transfers would lead to more than $5 billion in losses for the agriculture sector, whereas losses for valley-wide trading would be less than $2 billion.[17] Economic losses due to SGMA implementation are expected to be greatest for perennial tree crops.

Across the valley, SGMA is driving creative approaches to land and water management. Within the context of the San Joaquin Valley foodscape, such willingness to experiment and try new approaches presents two primary opportunities for nature-based regenerative agriculture solutions: (1) rebalancing water use to better provide farms with secure water supplies while creating and restoring habitat for native species on retired lands, and (2) managing productive lands in ways that provide wildlife benefits, such as on-farm recharge to replenish groundwater supplies. This can be done on seasonally fallowed fields or on active fields of compatible crops and serves the dual purpose of creating temporary wetland habitat for birds using the Pacific Flyway and recharging groundwater.

Taking agricultural land out of production presents significant opportunities for restoring habitat for important wildlife.

Restoring upland areas could meet the habitat needs of many of the most important species in the San Joaquin Valley, provided such restorations are strategically located in proximity to other important protected areas.[46] Doing this could allow for achieving target conservation goals on about half as much land as would be necessary if restoration was not strategically sited.

Nature-based solutions such as habitat restoration within the foodscape also stand to improve air and water quality by reducing dust and nitrous oxide emissions associated with agriculture and fallowed lands, as well as eliminating future fertilizer applications that could contribute to further nitrate contamination of groundwater. For some crops, such as almonds that depend on pollination, restoring upland habitat may provide critical habitat for pollinators that increase crop yields or make farmers less dependent on seasonal importing of bees.

Re-envisioning how the San Joaquin operates to support a vibrant farming community while also providing habitat for the fish and wildlife that live in the valley and its rivers will require large-scale investments and financial incentives, such as ecosystem services markets. By implementing nature-based solutions in the San Joaquin Valley Foodscape, both land and water stewardship can play a role in the region's recovery.

Farmer picking tea, Upper Tana River Basin, Kenya
© Nick Hall

Upper Tana River Basin
Foodscape

Innovate technical solutions for market-oriented smallholders

KENYA

LOCATION: North of Nairobi, Kenya
SIZE: 1 million hectares

SYNOPSIS

The Upper Tana River Basin foodscape in Kenya is a diverse, high-elevation smallholder production landscape that is an important source of food for the 9 million inhabitants of the greater Nairobi area. Farmers in the Upper Tana also export their crops — mostly to Europe —making this a smallholder farming landscape that is simultaneously crucial for local food demand in one of the most important urban centers in Africa, and a key supplier to international markets.

In addition to food, the watershed also provides drinking water for those 9 million people, as well as 50% of Kenya's electricity supply through a series of hydropower dams along the Tana River. But while Nairobi's place downstream from the Upper Tana means the city is relatively close to an important food supply, it also means that soil erosion within the watershed damages the hydroelectric and drinking water infrastructure that also supplies water and electricity to people in the greater Nairobi area.

UPPER TANA

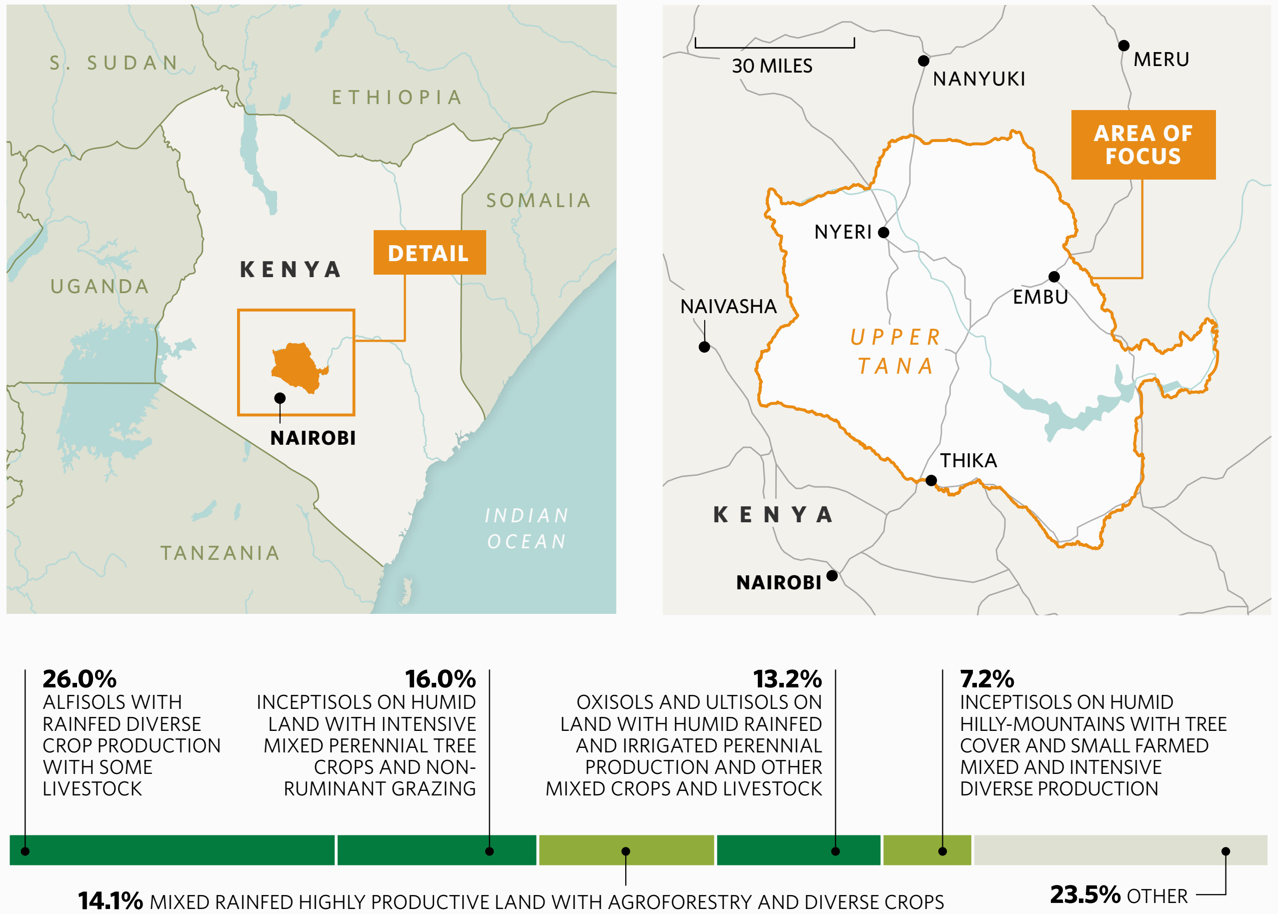

FIGURE 1. Map of Upper Tana River Basin foodscape. The bars represent the most extensive foodscape classes within the foodscape. The color of bars indicates the intensity groups corresponding to those classes: intensive production dominant (dark green) and mixed mosaic food cultivation (light green). The other category includes the classes that each made up <5% of the foodscape area.

This urban proximity offers an opportunity to reap the benefits of planning at the foodscape level because connecting nearby urban consumers of food and water with upstream suppliers can create economic opportunity while supporting sustainable land management within the watershed. In fact, one such market-based approach is already at work in the basin.

The Upper Tana-Nairobi Water Fund, an existing public-private partnership, shows how the right policies, conditions, and alignment of incentives can support changes in land management practices that reduce erosion. Briefly, a water fund is a mechanism to connect suppliers and consumers in ways that benefit both. In a water fund, downstream commercial and industrial water users invest in upstream conservation to lower sedimentation rates.

Water funds, like the one in the Upper Tana River Basin, show that market-based approaches are most effective when paired with innovation from the private sector and strong enabling conditions – policies and social norms, for example – that allow benefits to be shared equitably.

A silty Tana River, caused by erosion of agricultural soils, as it crosses the Chania Falls in Thika, Kenya
© Nick Hall

ABOUT THE FOODSCAPE

The Upper Tana River Basin foodscape, just north of Nairobi (FIGURE 1), is a classic example of a diversified, highland cropping system. The foodscape is composed of thousands of homesteads (shambas) – most smaller than 2 hectares – that typically include a small house, some outbuildings, and a patchwork of fields interspersed with coppices of trees that provide shade, firewood and fruit.

Farmers produce cereals, vegetables, fruits, coffee, tea, and livestock products such as milk and eggs on small parcels of land with relatively little mechanization and few agricultural inputs, and they export green beans, pineapple, coffee and tea mostly to Europe.

Life on the shamba moves with the rain: robust long rains followed by sporadic short rains, with dry spells in between, dictate when food can be grown. While some food is grown for a family's consumption — especially white maize, the key ingredient in ugali, a Kenyan staple — a good portion is sold in local markets, including in Nairobi.

In recent years, traditional subsistence crops, including maize, beans and tubers, are giving way to higher-value cash crops such as peppers, tomatoes and avocado, driven by demand in Europe and Nairobi. Tea and coffee have historically been the major cash crops in the higher elevation areas and remain widely cultivated.

CHALLENGES

"Maji ni uhai" – "water is life" in Swahili – and in the Upper Tana, water is a blessing that must be carefully managed. As rainfall varies, so does the Tana River, with downstream users concerned about maintaining a steady supply of clean water. For hydropower operators, the sediment that washes into the river from fields, roads and steep slopes threatens electricity production. For farmers, loss of topsoil also reduces crop productivity. As with most rainfed farming, dry years and longer dry spells associated with climate change cause crop losses.

Increased focus on market-oriented production creates economic opportunity but also exposes farmers to price volatility and creates disparities among farmers depending on their access to agricultural inputs, technical training and resources. Farmers, especially those in underrepresented social groups, such as women, lack crucial resources for market-oriented production. They may plant crops at the wrong time, without enough nutrients for optimal crop growth, or lose precious irrigation water to evaporation. Some farmers benefit from technology, such as mobile credit and digital agronomy, to support their farm enterprise. Yet others remain disconnected from improving techniques, technologies and other resources.

BENEFITS AND VALUE OF NATURE-BASED SOLUTIONS IN THE UPPER TANA RIVER BASIN FOODSCAPE

Nature-based solutions to the challenges in the Upper Tana River Basin foodscape fall into two categories: agronomic solutions to improve crop productivity, such as soil fertility management, and landscape solutions that minimize soil erosion and capture rainwater.

Though most erosion here comes from unpaved roads, incentivizing and encouraging farmers to adopt practices such as terracing, water collection basins (water pans), and agroforestry can help slow the movement of water and stabilize soils and keep them in place.

A farmer holds raw coffee beans
© Nick Hall

Terracing and the use of forage grasses such as Napier also help stabilize steeper slopes. Such high-quality forages also help boost milk yields in dairy cows, contributing to greater household income. Across broader areas, such erosion control measures could reduce erosion rates by up to 3 tons per hectare per year in high erosion areas of the foodscape. In some areas, the benefits could include up to 50% increases in crop yields.

Some practices provide both agronomic and erosion-reducing benefits. Water pans, which are collection basins to harvest runoff from roofs and roads, provide water for irrigation and drinking water for livestock while also reducing erosion. Irrigation allows farmers to grow higher-value horticultural crops during the dry season. Adding irrigated horticultural crops and agroforestry to an existing cash crop system could increase farm net income from around $800 to up to $2,000 per year in Muranga'a County, which is one of several counties in the Upper Tana River Basin (Supplementary Material,[1] Archetype B).

The Upper Tana Nairobi Water Fund has supported the installation of 14,000 water pans on 200,000 farms across the watershed. Looking at the same area from the holistic perspective of the foodscape also shows that reallocating more of the farm landscape to horticulture, by converting some timber, coffee and maize fields, could provide almost $400 in additional income per year per farm (Supplementary Material,[1] Archetype C).

Such crop switching to higher value crops creates an opportunity for targeted agronomic guidance across the foodscape around soil fertility and agronomy. Advances in soil testing and digital extension services have made it possible to tailor soil fertility and crop protection amendments to each field, removing technical constraints for optimizing for the highest value crops. Bringing these advances to the Upper Tana River Basin foodscape could enable farmers to move off the least productive, most unstable slopes, freeing up land for the rich biodiversity in the region and the return of native trees and shrubs that provide important habitat and further guard against erosion. In fact, incorporation of trees and shrubs into the foodscape provides multiple benefits, enabling farmers to capitalize on growing demand for fruit and timber, while sequestering carbon, reducing erosion and potentially providing additional habitat for biodiversity.

The Upper Tana is home to the Hinde's babbler (*Turdoides hindei*), whose global range is confined to the Upper Tana. *T. hindei* depends on shrubby vegetation on slopes for nesting habitat. With the loss of native habitat, the bird uses the invasive *Lantana camara*. Agroforestry and soil stabilization measures, including selecting the right plant species, can provide necessary habitat for this at-risk bird and may support greater biodiversity in the region.

The economic value of agroforestry is also important. Farms that convert half of coffee to fruit trees and timber agroforestry could increase income by around $1,000 per hectare per year (Supplementary Material,[1] Archetype A). The Upper Tana Nairobi Water Fund has already planted more than 3 million trees throughout the foodscape. Overall, the economic benefits of potential land-use transitions across the foodscape are significant (FIGURE 2).

At the scale of Murang'a County, which is a subset of the Upper Tana, incorporating more diversified crops into the existing maize/coffee/tea system could lead to $578 million per year of increased on-farm benefits. Even accounting for the cost of the public investment necessary to implement such land use transitions at the Murang'a County level, net benefits would be $326 million per year.

Many of these nature-based solutions – soil fertility management, crop diversification, and agroforestry – have been promoted for decades. Accelerating and broadening adoption rates has required efforts that combine economic incentives, shared benefits, public investment and enabling policies, and ongoing technological innovations, such as improved fertilizer blends targeted for soils in the region.

Efforts that combine public sector and private sector momentum, such as the Upper Tana-Nairobi Water Fund, are an important catalyst for adopting new behaviors and practices. The collaboration has specifically shown the value of outreach to underrepresented farmers such as women who traditionally lack access to material and technical resources.

AGGREGATION OF ARCHETYPES TO THE FOODSCAPE LEVEL

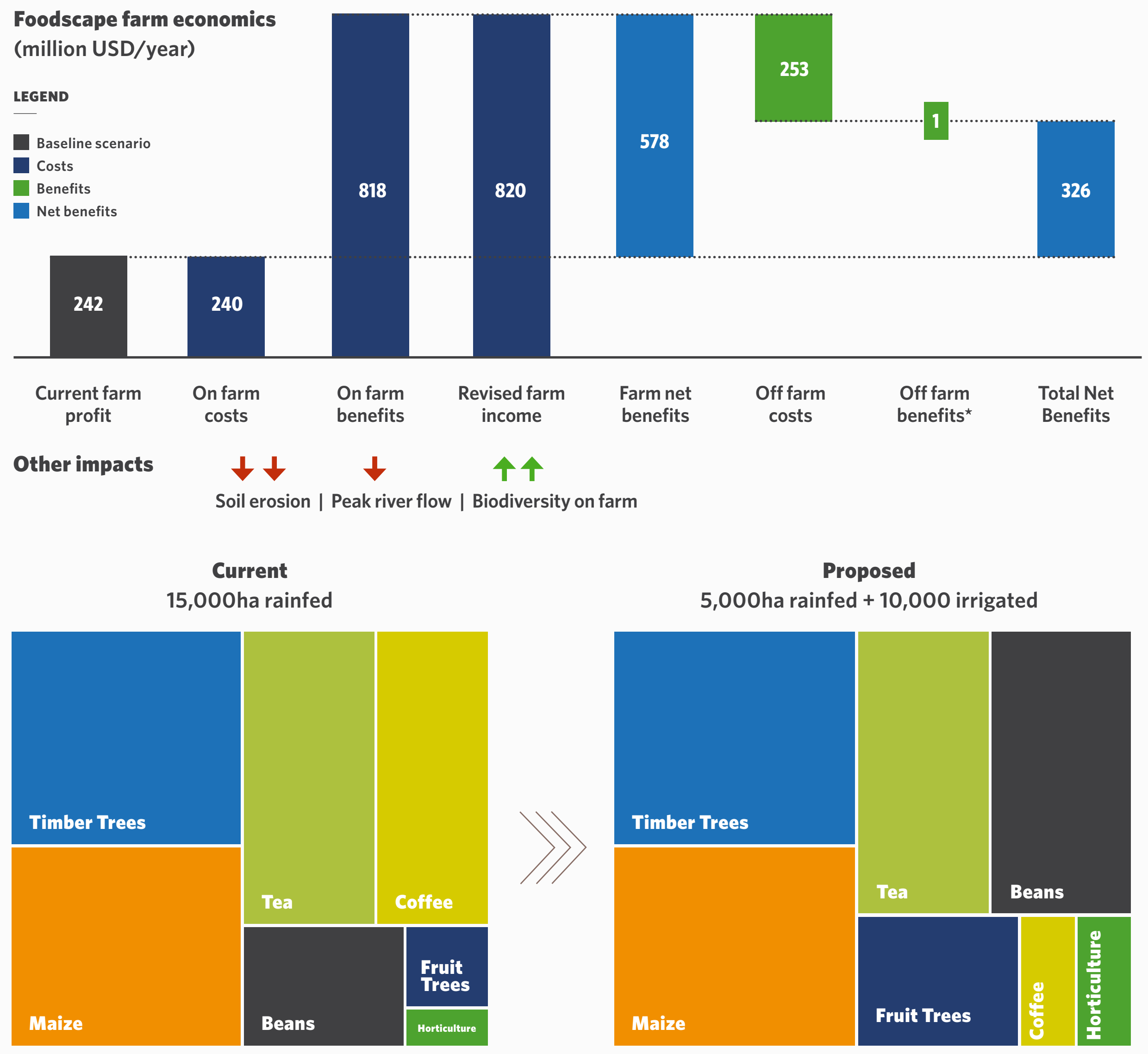

FIGURE 2. Summary of economic analyses for the Upper Tana River Basin foodscape. **Disaggregated costs & benefits toward $326 million net benefits from several farm archetypes:** Starting with baseline current farm profits (grey, far left), the diagram shows proposed future on farm benefits and costs (dark blue), totaling farm net benefits of $US 578 million (light blue, middle). Additional public off farm benefits and costs (light green) added to and subtracted from farm net benefits equals $US 326 million total net benefits (light blue, far right). Other impacts are qualitative assessments of other ecosystem service benefits. The change in area of nature-based solutions associated with the farm archetypes is represented in the boxes. See Supplementary Material for a description of methods.[1]

REFERENCES – INTRODUCTION

1. Willett, W. *et al.* Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet* **393**, 447–492 (2019).
2. Food and Land Use Coalition. *Growing Better: Ten Critical Transitions to Transform Food and Land Use*. https://www.foodandlandusecoalition.org/wp-content/uploads/2019/09/FOLU-GrowingBetter-GlobalReport.pdf (2019).
3. Leclère, D. et al. Bending the curve of terrestrial biodiversity needs an integrated strategy. Nature **585**, 551–556 (2020).
4. Tubiello, F. N. et al. Greenhouse gas emissions from food systems: building the evidence base. *Environ*. Res. Lett. **16**, 065007 (2021).
5. IPBES. *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. 1–56 (2019).
6. Benton, T. G., Bieg, C., Harwatt, H., Pudasaini, R. & Wellesley, L. F*ood system impacts on biodiversity loss: Three levers for system transformation in support of nature*. https://www.chathamhouse.org/sites/default/files/2021-02/2021-02-03-food-system-biodiversity-loss-benton-et-al_0.pdf (2021).
7. T*he State of Food Security and Nutrition in the World 202*1. (FAO, IFAD, UNICEF, WFP and WHO, 2021). doi:10.4060/cb4474en.
8. Frison, E. A. *From uniformity to diversity: a paradigm shift from industrial agriculture to diversified agroecological systems*. 1–96 https://cgspace.cgiar.org/handle/10568/75659 (2016).
9. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IPBES. *The IPBES assessment report on land degradation and restoration*. https://zenodo.org/record/3237392 (2018) doi:10.5281/ZENODO.3237392.
10. Deutz, A. e*t al. Financing Nature: Closing the global biodiversity financing gap*. https://www.paulsoninstitute.org/wp-content/uploads/2020/10/FINANCING-NATURE_Full-Report_Final-with-endorsements_101420.pdf (2020).
11. The Nature Conservancy & IIASA. *Foodscapes: Geospatial Methodologies*. (2021) doi:10.5281/ZENODO.5564644.

REFERENCES – SECTION 1

1. Conservancy, T. N. & IIASA. Foodscapes: Geospatial Methodologies. (2021) doi:10.5281/ZENODO.5564644.
2. United Nations Environment Programme. *Food Waste Index Report 2021*. 1–100 https://www.unep.org/resources/report/unep-food-waste-index-report-2021 (2021).
3. Wood, S. A., Smith, M. R., Fanzo, J., Remans, R. & DeFries, R. S. Trade and the equitability of global food nutrient distribution. *Nat Sustain* **1**, 34–37 (2018).
4. DeFries, R. *et al.* Metrics for land-scarce agriculture. *Science* **349**, 238–240 (2015).
5. Bogard, J. R., Marks, G. C., Wood, S. & Thilsted, S. H. Measuring nutritional quality of agricultural production systems: Application to fish production. *Global Food Security* **16**, 54–64 (2018).
6. Remans, R., Wood, S. A., Saha, N., Anderman, T. L. & DeFries, R. S. Measuring nutritional diversity of national food supplies. *Global Food Security* **3**, 174–182 (2014).
7. Remans, R. *et al*. Assessing Nutritional Diversity of Cropping Systems in African Villages. *PLoS ONE* **6**, e21235 (2011).
8. Wood, S. A. Nutritional functional trait diversity of crops in south-eastern Senegal. *J Appl Ecol* **55**, 81–91 (2018).
9. *Sustainability in action.* (2020). doi:10.4060/ca9229en.
10. Naylor, R. L. *et al.* Blue food demand across geographic and temporal scales. *Nat Commun* **12**, 5413 (2021).
11. Short, R. E. *et al.* Harnessing the diversity of small-scale actors is key to the future of aquatic food systems. *Nat Food* **2**, 733–741 (2021).
12. Cai, J. & Leung, P. *Short-term projection of global fish demand and supply gaps.* (Food and Agriculture Organization of the United Nations, 2017).
13. Oyinlola, M. A., Reygondeau, G., Wabnitz, C. C. C., Troell, M. & Cheung, W. W. L. Global estimation of areas with suitable environmental conditions for mariculture species. *PLoS ONE* **13**, e0191086 (2018).
14. Froehlich, H. E., Afflerbach, J. C., Frazier, M. & Halpern, B. S. Blue Growth Potential to Mitigate Climate Change through Seaweed Offsetting. *Current Biology* **29**, 3087-3093.e3 (2019).
15. Costello, C. *et al.* The future of food from the sea. *Nature* **588**, 95–100 (2020).
16. Froehlich, H. E. *et al.* Mind the gap between ICES nations' future seafood consumption and aquaculture production. *ICES Journal of Marine Science* **78**, 468–477 (2021).
17. U.S. Geological Survey *et al.* A Three-Dimensional Mapping of the Ocean Based on Environmental Data. *Oceanog.* **30**, 90–103 (2017).
18. *Investing in agriculture for a better future.* (FAO, 2012).
19. Garibaldi, L. & Limongelli, L. *Trends in oceanic captures and clustering of large marine ecosystems: two studies based on the FAO capture database.* (Food and Agriculture Organization of the United Nations, 2003).
20. Pauly, D. *et al.* Fisheries in Large Marine Ecosystems: Descriptions and Diagnoses. in *The UNEP Large Marine Ecosystem Report: a Perspective on Changing Conditions in LMEs of the World's Regional Seas* 23–40 (United Nations Environment Programme, 2008).
21. Schiller, L., Bailey, M., Jacquet, J. & Sala, E. High seas fisheries play a negligible role in addressing global food security. *Sci. Adv.* **4**, eaat8351 (2018).
22. Costello, C. *et al.* Global fishery prospects under contrasting management regimes. *Proc Natl Acad Sci USA* **113**, 5125–5129 (2016).
23. World Bank. *The Sunken Billions Revisited: Progress and Challenges in Global Marine Fisheries.* (Washington, DC: World Bank, 2017). doi:10.1596/978-1-4648-0919-4.
24. Shepon, A. *et al.* Reorientation of aquaculture production systems can reduce environmental impacts and improve nutrition security in Bangladesh. *Nat Food* **1**, 640–647 (2020).
25. Golden, C. D. *et al.* Does Aquaculture Support the Needs of Nutritionally Vulnerable Nations? *Front. Mar. Sci.* **4**, 159 (2017).
26. Hilborn, R., Banobi, J., Hall, S. J., Pucylowski, T. & Walsworth, T. E. The environmental cost of animal source foods. *Front Ecol Environ* **16**, 329–335 (2018).
27. Poore, J. & Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987–992 (2018).
28. Fluet-Chouinard, E., Funge-Smith, S. & McIntyre, P. B. Global hidden harvest of freshwater fish revealed by household surveys. *Proc Natl Acad Sci USA* **115**, 7623–7628 (2018).
29. Hortle, K. & Bamrungrach, P. *Fisheries Habitat and Yield in the Lower Mekong Basin.* 80 https://www.mrcmekong.org/assets/Publications/technical/tech-No47-Fisheries-habitat-n-yield-in-the-MB.pdf (2015).
30. Youn, S.-J. *et al.* Inland capture fishery contributions to global food security and threats to their future. *Global Food Security* **3**, 142–148 (2014).
31. O'Meara, L. *et al.* Inland fisheries critical for the diet quality of young children in sub-Saharan Africa. *Global Food Security* **28**, 100483 (2021).
32. Vinceti, B. *et al.* The contributions of forest foods to sustainable diets. *Unasylva* **64**, 54–64 (2013).
33. Gergel, S. E. *et al.* Conceptual Links between Landscape Diversity and Diet Diversity: A Roadmap for Transdisciplinary Research. *BioScience* **70**, 563–575 (2020).
34. Rasmussen, L. V. *et al.* Forest pattern, not just amount, influences dietary quality in five African countries. *Global Food Security* **25**, 100331 (2020).
35. Powell, B., Hall, J. & Johns, T. Forest cover, use and dietary intake in the East Usambara Mountains, Tanzania. *int. forest. rev.* **13**, 305–317 (2011).
36. Powell, B., Maundu, P., Kuhnlein, H. V. & Johns, T. Wild Foods from Farm and Forest in the East Usambara Mountains, Tanzania. *Ecology of Food and Nutrition* **52**, 451–478 (2013).
37. Broegaard, R. B. *et al.* Wild food collection and nutrition under commercial agriculture expansion in agriculture-forest landscapes. *Forest Policy and Economics* **84**, 92–101 (2017).
38. Tata, C. Y., Ickowitz, A., Powell, B. & Colecraft, E. K. Dietary intake, forest foods, and anemia in Southwest Cameroon. *PLoS ONE* **14**, e0215281 (2019).
39. Benítez-López, A., Santini, L., Schipper, A. M., Busana, M. & Huijbregts, M. A. J. Intact but empty forests? Patterns of hunting-induced mammal defaunation in the tropics. *PLoS Biol* **17**, e3000247 (2019).
40. Brashares, J. S. Bushmeat Hunting, Wildlife Declines, and Fish Supply in West Africa. *Science* **306**, 1180–1183 (2004).
41. World Bank. *Urban Agriculture: Findings from Four City Case Studies.* (2013).
42. American Planning Association. Urban Agriculture. https://planning.org/knowledgebase/urbanagriculture/#:~:text=Urban%20Agriculture%201%20Urban%20Agriculture.%20The%20growing%20awareness,Urban%20Agriculture.%20...%203%20Regulating%20Urban%20Agriculture.%20.
43. Centers for Disease Control and Prevention. Land Use Planning and Urban/Peri-Urban Agriculture. CDC - Healthy Places - Healthy Food - Land Use Planning and Urban/Peri-Urban Agriculture (2010).

REFERENCES – SECTION 2

1. IPBES. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. https://zenodo.org/record/3831673 (2019) doi:10.5281/ZENODO.3831673.
2. Kremen, C. & Merenlender, A. M. Landscapes that work for biodiversity and people. *Science* **362**, eaau6020 (2018).
3. Klein, A.-M. *et al.* Importance of pollinators in changing landscapes for world crops. *Proc. R. Soc. B*. **274**, 303–313 (2007).
4. Lehmann, J., Bossio, D. A., Kögel-Knabner, I. & Rillig, M. C. The concept and future prospects of soil health. *Nat Rev Earth Environ* **1**, 544–553 (2020).
5. Castañeda-Álvarez, N. P. *et al.* Global conservation priorities for crop wild relatives. *Nature Plants* **2**, 16022 (2016).
6. Deutsch, C. A. *et al.* Increase in crop losses to insect pests in a warming climate. *Science* **361**, 916–919 (2018).
7. Jung, M. *et al.* Areas of global importance for conserving terrestrial biodiversity, carbon and water. Nat Ecol Evol (2021) doi:10.1038/s41559-021-01528-7.
8. Nowosad, J., Stepinski, T. F. & Netzel, P. Global assessment and mapping of changes in mesoscale landscapes: 1992–2015. *International Journal of Applied Earth Observation and Geoinformation* **78**, 332–340 (2019).
9. Bunn, S. E. & Arthington, A. H. Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity. *Environmental Management* **30**, 492–507 (2002).
10. Benítez-López, A., Santini, L., Schipper, A. M., Busana, M. & Huijbregts, M. A. J. Intact but empty forests? Patterns of hunting-induced mammal defaunation in the tropics. *PLoS Biol* **17**, e3000247 (2019).
11. Sanderman, J., Hengl, T. & Fiske, G. J. Soil carbon debt of 12,000 years of human land use. *Proc Natl Acad Sci USA* **114**, 9575–9580 (2017).
12. Borrelli, P. *et al.* An assessment of the global impact of 21st century land use change on soil erosion. *Nat Commun* **8**, 2013 (2017).
13. Reusser, L., Bierman, P. & Rood, D. Quantifying human impacts on rates of erosion and sediment transport at a landscape scale. *Geology* **43**, 171–174 (2015).
14. Tubiello, F. N. *et al.* Greenhouse gas emissions from food systems: building the evidence base. *Environ. Res. Lett.* **16**, 065007 (2021).
15. The Nature Conservancy & IIASA. Foodscapes: Geospatial Methodologies. (2021) doi:10.5281/ZENODO.5564644.
16. Diaz, R. J. & Rosenberg, R. Spreading Dead Zones and Consequences for Marine Ecosystems. *Science* **321**, 926–929 (2008).
17. Maggi, F., Tang, F. H. M., la Cecilia, D. & McBratney, A. PEST-CHEMGRIDS, global gridded maps of the top 20 crop-specific pesticide application rates from 2015 to 2025. *Sci Data* **6**, 170 (2019).
18. McLellan, E. L. *et al.* The Nitrogen Balancing Act: Tracking the Environmental Performance of Food Production. *BioScience* **68**, 194–203 (2018).
19. Beck, M. W. *et al.* Oyster Reefs at Risk and Recommendations for Conservation, Restoration, and Management. *BioScience* **61**, 107–116 (2011).
20. Dunic, J. C., Brown, C. J., Connolly, R. M., Turschwell, M. P. & Côté, I. M. Long-term declines and recovery of meadow area across the world's seagrass bioregions. Glob. *Change Biol.* **27**, 4096–4109 (2021).
21. Polidoro, B. A. *et al.* The Loss of Species: Mangrove Extinction Risk and Geographic Areas of Global Concern. *PLoS ONE* **5**, e10095 (2010).
22. Krumhansl, K. A. *et al.* Global patterns of kelp forest change over the past half-century. *Proc Natl Acad Sci USA* **113**, 13785–13790 (2016).
23. Eddy, T. D. *et al.* Global decline in capacity of coral reefs to provide ecosystem services. *One Earth* **4**, 1278–1285 (2021).
24. Hoegh-Guldberg, O., Kennedy, E. V., Beyer, H. L., McClennen, C. & Possingham, H. P. Securing a Long-term Future for Coral Reefs. *Trends in Ecology & Evolution* **33**, 936–944 (2018).
25. Halpern, B. S. *et al.* Recent pace of change in human impact on the world's ocean. *Sci Rep* **9**, 11609 (2019).
26. Gilman, E. *et al.* Highest risk abandoned, lost and discarded fishing gear. *Sci Rep* **11**, 7195 (2021).
27. Sustainability in action. (2020). doi:10.4060/ca9229en.
28. Barange, M. *et al.* Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. (2018).
29. Gephart, J. A., Rovenskaya, E., Dieckmann, U., Pace, M. L. & Brännström, Å. Vulnerability to shocks in the global seafood trade network. *Environ. Res. Lett.* **11**, 035008 (2016).
30. Reverter, M. *et al.* Aquaculture at the crossroads of global warming and antimicrobial resistance. *Nat Commun* **11**, 1870 (2020).

REFERENCES – SECTION 3

1. Food and Land Use Coalition. *Growing Better: Ten Critical Transitions to Transform Food and Land Use.* https://www.foodandlandusecoalition.org/wp-content/uploads/2019/09/FOLU-GrowingBetter-GlobalReport.pdf (2019).
2. Queiroz, C. *et al.* Investment in resilient food systems in the most vulnerable and fragile regions is critical. *Nat Food* **2**, 546–551 (2021).
3. Lesiv, M. *et al.* Estimating the global distribution of field size using crowdsourcing. *Glob Change Biol* **25**, 174–186 (2019).
4. Yu, Q. *et al.* A cultivated planet in 2010 – Part 2: The global gridded agricultural-production maps. *Earth Syst. Sci. Data* **12**, 3545–3572 (2020).
5. Garibaldi, L. A. *et al.* Working landscapes need at least 20% native habitat. *CONSERVATION LETTERS* **14**, (2021).
6. Dinerstein, E. *et al.* An Ecoregion-Based Approach to Protecting Half the Terrestrial Realm. *BioScience* **67**, 534–545 (2017).
7. Jose, S. Agroforestry for ecosystem services and environmental benefits: an overview. *Agroforest Syst* **76**, 1–10 (2009).
8. Bazié, H. R., Bayala, J., Zombré, G., Sanou, J. & Ilstedt, U. Separating competition-related factors limiting crop performance in an agroforestry parkland system in Burkina Faso. *Agroforest Syst* **84**, 377–388 (2012).
9. Staton, T., Breeze, T. D., Walters, R. J., Smith, J. & Girling, R. D. Productivity, biodiversity trade-offs, and farm income in an agroforestry versus an arable system. *Ecological Economics* **191**, 107214 (2022).
10. Teixeira, F. Z. *et al.* Perceived ecosystem services (ES) and ecosystem disservices (EDS) from trees: insights from three case studies in Brazil and France. *Landscape Ecol* **34**, 1583–1600 (2019).
11. Cardinael, R. *et al.* Revisiting IPCC Tier 1 coefficients for soil organic and biomass carbon storage in agroforestry systems. *Environ. Res. Lett.* **13**, 124020 (2018).
12. Trabucco, A. & Zomer, R. J. Global aridity index and potential evapotranspiration (ET0) climate database v2. *CGIAR Consort Spat Inf* **10**, (2018).
13. Lehmann, J., Bossio, D. A., Kögel-Knabner, I. & Rillig, M. C. The concept and future prospects of soil health. *Nat Rev Earth Environ* **1**, 544–553 (2020).
14. Porwollik, V., Rolinski, S., Heinke, J. & Müller, C. Generating a rule-based global gridded tillage dataset. *Earth Syst. Sci. Data* **11**, 823–843 (2019).
15. Sanderman, J. *et al.* Soils Revealed soil carbon futures. (2020) doi:10.7910/DVN/HA17D3.
16. Zhang, B. *et al.* Global manure nitrogen production and application in cropland during 1860–2014: a 5 arcmin gridded global dataset for Earth system modeling. *Earth Syst. Sci. Data* **9**, 667–678 (2017).
17. Grafton, R. Q. *et al.* The paradox of irrigation efficiency. *Science* **361**, 748–750 (2018).
18. Brauman, K. A., Richter, B. D., Postel, S., Malsy, M. & Flörke, M. Water depletion: An improved metric for incorporating seasonal and dry-year water scarcity into water risk assessments. *Elem Sci Anth* **4**, 000083 (2016).
19. Jägermeyr, J. *et al.* Water savings potentials of irrigation systems: global simulation of processes and linkages. *Hydrol. Earth Syst. Sci.* **19**, 3073–3091 (2015).
20. Chiarelli, D. D. *et al.* The green and blue crop water requirement WATNEEDS model and its global gridded outputs. *Sci Data* **7**, 273 (2020).
21. Costello, C. *et al.* The future of food from the sea. *Nature* **588**, 95–100 (2020).
22. Gaines, S. D. *et al.* Improved fisheries management could offset many negative effects of climate change. *Sci. Adv.* **4**, eaao1378 (2018).
23. Froehlich, H. E., Afflerbach, J. C., Frazier, M. & Halpern, B. S. Blue Growth Potential to Mitigate Climate Change through Seaweed Offsetting. *Current Biology* **29**, 3087-3093.e3 (2019).
24. Theuerkauf, S. J. *et al.* Habitat value of bivalve shellfish and seaweed aquaculture for fish and invertebrates: Pathways, synthesis and next steps. *Rev Aquacult* raq.12584 (2021) doi:10.1111/raq.12584.
25. Theuerkauf, S. J. *et al.* A global spatial analysis reveals where marine aquaculture can benefit nature and people. *PLoS ONE* **14**, e0222282 (2019).
26. Lynch, J., Cain, M., Pierrehumbert, R. & Allen, M. Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. *Environ. Res. Lett.* **15**, 044023 (2020).
27. Costa, Jr., C., Wironen, M., Racette, K. & Wollenberg, E. *Global Warming Potential* (GWP*): Understanding the implications for mitigating methane emissions in agriculture.* 1–7 https://cgspace.cgiar.org/bitstream/handle/10568/114632/2021_Info%20Note%20GWP_FINAL.pdf?sequence=6&isAllowed=y (2021).
28. Wells, J. C. *et al.* The double burden of malnutrition: aetiological pathways and consequences for health. *The Lancet* **395**, 75–88 (2020).
29. Willett, W. *et al.* Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet* **393**, 447–492 (2019).
30. Oldfield, E. E., Bradford, M. A. & Wood, S. A. Global meta-analysis of the relationship between soil organic matter and crop yields. *SOIL* **5**, 15–32 (2019).
31. Oldfield, E. E., Wood, S. A. & Bradford, M. A. Direct evidence using a controlled greenhouse study for threshold effects of soil organic matter on crop growth. *Ecol Appl* **30**, (2020).
32. Wood, S. A., Tirfessa, D. & Baudron, F. Soil organic matter underlies crop nutritional quality and productivity in smallholder agriculture. *Agriculture, Ecosystems & Environment* **266**, 100–108 (2018).
33. Kane, D. A., Bradford, M. A., Fuller, E., Oldfield, E. E. & Wood, S. A. Soil organic matter protects US maize yields and lowers crop insurance payouts under drought. *Environ. Res. Lett.* **16**, 044018 (2021).
34. Marcillo, G. S. & Miguez, F. E. Corn yield response to winter cover crops: An updated meta-analysis. *Journal of Soil and Water Conservation* **72**, 226–239 (2017).
35. Murphy, K. M., Hoagland, L. A., Reeves, P. G., Baik, B.-K. & Jones, S. S. Nutritional and quality characteristics expressed in 31 perennial wheat breeding lines. *Renew. Agric. Food Syst.* **24**, 285–292 (2009).
36. Seufert, V. & Ramankutty, N. Many shades of gray – The context-dependent performance of organic agriculture. *Sci. Adv.* **3**, e1602638 (2017).
37. Pimentel, D. *et al.* Annual vs. perennial grain production. Agriculture, *Ecosystems & Environment* **161**, 1–9 (2012).
38. 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).

REFERENCES – SECTION 5

1. Simons, Rupert *et al.* foodscapes : Economic Methodology. (2021) doi:10.5281/ZENODO.5550292.
2. Hoekstra, J. M., Boucher, T. M., Ricketts, T. H. & Roberts, C. Confronting a biome crisis: global disparities of habitat loss and protection: Confronting a biome crisis. *Ecology Letters* **8**, 23–29 (2004).
3. Fernandez-Gimenez, M. E. THE ROLE OF MONGOLIAN NOMADIC PASTORALISTS' ECOLOGICAL KNOWLEDGE IN RANGELAND MANAGEMENT. *Ecological Applications* **10**, 1318–1326 (2000).
4. Upton, C. "Custom" and Contestation: Land Reform in Post-Socialist Mongolia. *World Development* **37**, 1400–1410 (2009).
5. Nixson, F. & Walters, B. Privatization, Income Distribution, and Poverty: The Mongolian Experience. *World Development* **34**, 1557–1579 (2006).
6. Fernández-Giménez, M. E. THE EFFECTS OF LIVESTOCK PRIVATISATION ON PASTORAL LAND USE AND LAND TENURE IN POST-SOCIALIST MONGOLIA. *Nomadic Peoples* **5**, 49–66 (2001).
7. Nandintsetseg, B. *et al.* Risk and vulnerability of Mongolian grasslands under climate change. *Environ. Res. Lett.* **16**, 034035 (2021).
8. Marin, A. Riders under storms: Contributions of nomadic herders' observations to analysing climate change in Mongolia. *Global Environmental Change* **20**, 162–176 (2010).
9. Murphy, D. Disaster, Mobility, and the Moral Economy of Exchange in Mongolian Pastoralism. *Nomadic Peoples* **22**, 304–329 (2018).
10. Ahearn, A. & Bumochir, D. Contradictions in Schooling Children among Mongolian Pastoralists. *Human Organization* **75**, 87–96 (2016).
11. Murphy, D. J. From kin to contract: labor, work and the production of authority in rural Mongolia. *The Journal of Peasant Studies* **42**, 397–424 (2015).
12. Fernández-Giménez, M. E. *et al.* Exploring linked ecological and cultural tipping points in Mongolia. *Anthropocene* **17**, 46–69 (2017).
13. IRIM. *Conserving forest steppe ecosystems and endangered species through community-led network: Endline study report.* **55** (2021).
14. Leisher, C., Hess, S., Boucher, T. M., Beukering, P. van & Sanjayan, M. Measuring the Impacts of Community-based Grasslands Management in Mongolia's Gobi. *PLOS ONE* **7**, e30991 (2012).
15. Upton, C. Adaptive capacity and institutional evolution in contemporary pastoral societies. *Applied Geography* **33**, 135–141 (2012).
16. Baivaland, B. & Fernández-Giménez, M. E. MEANINGFUL LEARNING FOR RESILIENCE-BUILDING AMONG MONGOLIAN PASTORALISTS. *Nomadic Peoples* **16**, 53–77 (2012).
17. Ulambayar, T. & Fernández-Giménez, M. E. How Community-Based Rangeland Management Achieves Positive Social Outcomes In Mongolia: A Moderated Mediation Analysis. *Land Use Policy* **82**, 93–104 (2019).
18. Fernández-Giménez, M. E., Batkhishig, B., Batbuyan, B. & Ulambayar, T. Lessons from the Dzud: Community-Based Rangeland Management Increases the Adaptive Capacity of Mongolian Herders to Winter Disasters. *World Development* **68**, 48–65 (2015).
19. Fernández-Giménez, M. E., Batkhishig, B. & Batbuyan, B. Cross-boundary and cross-level dynamics increase vulnerability to severe winter disasters (dzud) in Mongolia. *Global Environmental Change* **22**, 836–851 (2012).
20. Vincent, A., Stanley, A. & Ring, J. *Hidden champion of the ocean: Seaweed as a growth engine for a sustainable European future.* https://www.seaweedeurope.com/wp-content/uploads/2020/10/Seaweed_for_Europe-Hidden_Champion_of_the_ocean-Report.pdf (2020).
21. Spalding, M. D. *et al.* Marine Ecoregions of the World: A Bioregionalization of Coastal and Shelf Areas. *BioScience* **57**, 573–583 (2007).
22. Sinner, J. *et al.* Measuring social licence: What and who determines public acceptability of aquaculture in New Zealand? *Aquaculture* **521**, 734973 (2020).
23. New Zealand, Ministry for the Environment, New Zealand, Statistics New Zealand, & Our marine environment 2019. Summary. *Our marine environment* 2019. (2019).
24. Troell, M. *et al.* Does aquaculture add resilience to the global food system? *Proc Natl Acad Sci USA* **111**, 13257–13263 (2014).
25. Gephart, J. A., Rovenskaya, E., Dieckmann, U., Pace, M. L. & Brännström, Å. Vulnerability to shocks in the global seafood trade network. *Environ. Res. Lett.* **11**, 035008 (2016).
26. New Zealand Government. *The New Zealand Government Aquaculture Strategy.* https://www.mpi.govt.nz/dmsdocument/15895-The-Governments-Aquaculture-Strategy-to-2025 (2019).
27. Petersen, J. K., Saurel, C., Nielsen, P. & Timmermann, K. The use of shellfish for eutrophication control. *Aquacult Int* **24**, 857–878 (2016).
28. Xiao, X. *et al.* Nutrient removal from Chinese coastal waters by large-scale seaweed aquaculture. *Sci Rep* **7**, 46613 (2017).
29. Theuerkauf, S. J. *et al.* A global spatial analysis reveals where marine aquaculture can benefit nature and people. *PLoS ONE* **14**, e0222282 (2019).
30. Xiao, X. *et al.* Seaweed farms provide refugia from ocean acidification. *Science of The Total Environment* **776**, 145192 (2021).
31. Norrie, C., Dunphy, B., Roughan, M., Weppe, S. & Lundquist, C. Spill-over from aquaculture may provide a larval subsidy for the restoration of mussel reefs. Aquaculture Environment Interactions **12**, 231–249 (2020).
32. Barrett, L. T., Swearer, S. E. & Dempster, T. Impacts of marine and freshwater aquaculture on wildlife: a global meta-analysis. *Rev Aquacult* **11**, 1022–1044 (2019).
33. Theuerkauf, S. J. *et al.* Habitat value of bivalve shellfish and seaweed aquaculture for fish and invertebrates: Pathways, synthesis and next steps. *Rev Aquacult* raq.12584 (2021) doi:10.1111/raq.12584.
34. Kellogg, M., Cornwell, J., Owens, M. & Paynter, K. Denitrification and nutrient assimilation on a restored oyster reef. *Mar. Ecol. Prog. Ser.* **480**, 1–19 (2013).
35. Ramsar. Inner Niger Delta. https://www.ramsar.org/sites/default/files/documents/library/wwd2004_rpt_mali_press_e.pdf (2004).
36. APESS. *Élément de bilan du soutien public à l'élevage au Mali depuis Maputo.* https://doczz.fr/doc/1919455/%C3%A9l%C3%A9ments-de-bilan-du-soutien-public-%C3%A0-l-%C3%A9levage-au-mali-d... (2014).
37. WFP. *Satellite imagery to support WFP emergency response.* https://docs.wfp.org/api/documents/WFP-0000115730/download/ (2020).
38. Vatta, K. Sustainability of Groundwater Use in Punjab Agriculture: Issues and Options. in *Natural Resource Management: Ecological Perspectives* (eds. Peshin, R. & Dhawan, A. K.) 19–30 (Springer International Publishing, 2019). doi:10.1007/978-3-319-99768-1_2.
39. Beig, G. *et al.* Objective evaluation of stubble emission of North India and quantifying its impact on air quality of Delhi. *Science of The Total Environment* **709**, 136126 (2020).
40. Davis, K. F. *et al.* Alternative cereals can improve water use and nutrient supply in India. *Sci. Adv.* **4**, eaao1108 (2018).
41. Hanak, E. *et al. Water and the future of the San Joaquin Valley.* https://www.ppic.org/wp-content/uploads/water-and-the-future-of-the-san-joaquin-valley-february-2019.pdf (2019).

42. USDA. 2019 *California Tomato Processing Report.* https://www.nass.usda.gov/Statistics_by_State/California/Publications/Specialty_and_Other_Releases/Tomatoes/2019/201905ptom.pdf (2019).
43. Williams, D. *et al. Recovery plan for upland species of the San Joaquin Valley, California.* (1998).
44. MacEwan, D., Howitt, R. & Medellín-Azuara, J. Combining Physical and Behavioral Response to Salinity. *Water Econs. Policy* **02**, 1650010 (2016).
45. US EPA. Current Nonattainment Counties for All Criteria Pollutants. in *Green Book* (US Environmental Protection Agency, 2021).
46. Bryant, B. P. *et al.* Shaping Land Use Change and Ecosystem Restoration in a Water-Stressed Agricultural Landscape to Achieve Multiple Benefits. *Front. Sustain. Food Syst.* **4**, 138 (2020).

Annex 1

Map Key

AREAS WITH LITTLE OR ONLY SUBSISTENCE FOOD PRODUCTION

ENTISOLS ON PLAINS WITH BARE LAND, LITTLE FOOD PRODUCTION AND GRASS COVER

ENTISOLS ON PLAINS WITH GRAZED BARE LAND AND GRASS COVER

ENTISOLS ON PLAINS WITH BARE LAND AND SCATTERED MIXED CROP PRODUCTION AND LOW NUTRIENT APPLICATION RATE

ENTISOLS ON DRY PLAINS AND LARGE CULTIVATED FIELDS AND LIVESTOCK

ENTISOLS ON DRY RAINFED PLAINS WITH LEGUMES AND PULSES PRODUCTION AND OCCASIONALLY OTHER CROPS

ENTISOLS ON DRY PLAINS AND BARE LAND WITH MIXED IRRIGATED CROP PRODUCTION

ENTISOLS ON DRY PLAINS AND BARE LAND WITH IRRIGATED VEGETABLE PRODUCTION AND HIGH NUTRIENT APPLICATION RATES

INCEPTISOLS ON HUMID HILLY TREE-COVERED LAND WITH SCATTERED CROP PRODUCTION

INCEPTISOLS ON HUMID MOUNTAINOUS LAND WITH TREE COVER AND SCATTERED MIXED CROP PRODUCTION

INCEPTISOLS ON HUMID HILLY-MOUNTAINS WITH TREE COVER AND SMALL FARMED MIXED AND INTENSIVE DIVERSE PRODUCTION

INCEPTISOLS ON HUMID FORESTED HILLS WITH INTENSIVE MIXED CROP PRODUCTION AND GRAZING

INCEPTISOLS ON HUMID HILLY MIXED TREE-COVERED LAND WITH RAINFED PERENNIAL CROPS AND OTHER LIVESTOCK

MIXED RAINFED HIGHLY PRODUCTIVE LAND WITH AGROFORESTRY AND DIVERSE CROPS

INCEPTISOLS ON HUMID LAND WITH INTENSIVE MIXED PERENNIAL TREE CROPS AND NON-RUMINANT GRAZING

INCEPTISOLS ON HUMID HILLY LAND WITH INTENSIVE MIXED LIVESTOCK AND OTHER CROPS GROWN WITH HIGH NUTRIENT APPLICATION RATES

MIXED URBAN AND PERI-URBAN AREAS WITH SOME AGRICULTURE AND LIVESTOCK

PERI-URBAN AREAS WITH MARGINAL AGRICULTURE AND LIVESTOCK

PERI-URBAN AREA INTERSPERSED WITH INTENSIVE IRRIGATED AGRICULTURE AND LIVESTOCK

MOLLISOLS IN MOUNTAINOUS BARE AREAS WITH LITTLE CROP PRODUCTION AND GRAZING

MOLLISOLS IN MOUNTAINOUS-HILLY AREAS WITH LOW DENSITY LIVESTOCK GRAZING AND SCATTERED CROP PRODUCTION

MOLLISOLS IN MOUNTAINOUS-HILLY CULTIVATED LAND WITH GRAZING RUMINANTS AND RAINFED MIXED CROPS

MOLLISOLS IN HILLY CONVENTIONALLY TILLAGED CULTIVATED LAND WITH INTERSPERSED GRAZING

MOLLISOLS AND INCEPTISOLS IN PLAINS WITH IRRIGATED INTENSIVE CROP PRODUCTION

MOLLISOLS IN PLAINS WITH INTENSIVE IRRIGATED CEREAL AND OIL CROP PRODUCTION AND HIGH NUTRIENT APPLICATION RATES

MOLLISOLS IN INTENSIVE RAINFED CEREAL AND OIL CROP PRODUCING LAND WITH HIGH NUTRIENT APPLICATION RATES

MOLLISOLS IN PLAINS WITH INTENSIVE RAINFED LARGE FIELD WITH CEREAL AND OIL CROP PRODUCTION

MOLLISOLS IN PLAINS WITH INTENSIVE RAINFED CEREAL AND OIL CROP PRODUCING LAND THAT IS SINGLE CROPPED

VERTISOLS IN PLAINS WITH GRAZED SHRUBBY LAND AND SCATTERED MIXED CROP PRODUCTION

VERTISOLS IN PLAINS DIVERSELY CULTIVATED LAND AND INTERSPERSED GRAZING

VERTISOLS IN PLAINS WITH MIXED CROP AND LIVESTOCK PRODUCTION

VERTISOLS IN PLAINS WITH MIXED IRRIGATED AND RAINFED PRODUCTION WITH MIXED CROP PRODUCTION

VERTISOLS IN PLAINS WITH RAINFED INTENSIVELY CULTIVATED LAND WITH MIXED PRODUCTION AND SPARSE GRAZING

VERTISOLS IN PLAINS WITH LARGER INTENSIVELY CULTIVATED FIELDS WITH REDUCED TILLAGE

INCEPTISOLS ON BARE GRASSY LAND WITH SCATTERED GRAZING

INCEPTISOLS ON MIXED FOREST AND GRASSLAND

INCEPTISOLS IN HILLY GRASSY LAND WITH SCATTERED GRAZING AND MARGINAL CROP PRODUCTION

INCEPTISOLS IN MOUNTAINOUS BARE LAND WITH SMALL FIELDS AND TRADITIONAL TILLAGE

INCEPTISOLS IN FORESTED LAND WITH FEW SCATTERED LARGE FARMS AND LOW CROP DIVERSITY

INCEPTISOLS IN HILLY LAND WITH MIXED PRODUCTION OF CONVENTIONAL TILLAGE AND HIGH NUTRIENT APPLICATION

INCEPTISOLS IN ARID HILLY LAND WITH RAINFED CEREAL AND LEGUME PRODUCTION AND OTHER LIVESTOCK

INCEPTISOLS IN HILLS AND MOUNTAINS WITH IRRIGATED INTENSIVE MIXED CROP PRODUCTION

INCEPTISOLS IN HILLY SHRUBLAND WITH IRRIGATED INTENSIVE MIXED CROP PRODUCTION AND HIGH NUTRIENT APPLICATION

ALFISOLS IN PLAINS AND GRASSLANDS WITH LITTLE CROP PRODUCTION AND GRAZING

ALFISOLS IN SHRUBBY PLAINS THAT ARE GRAZED WITH SCATTERED CROPLAND

ALFISOLS IN MIXED FOOD PRODUCTION LANDSCAPES WITH SCATTERED GRAZING

ALFISOLS IN MIXED DIVERSE CROP SYSTEMS ON SMALL FIELDS WITH SOME LIVESTOCK AND AGROFORESTRY AND LOW NUTRIENT APPLICATION RATES

ALFISOLS WITH MIXED CROP PRODUCTION, SOME RUMINANTS, AND HIGHER NUTRIENT APPLICATION RATES

ALFISOLS WITH RAINFED CROP PRODUCTION ON LARGE FIELDS WITH SOME LIVESTOCK

ALFISOLS WITH RAINFED DIVERSE CROP PRODUCTION WITH SOME LIVESTOCK

ALFISOLS WITH IRRIGATED INTENSIVE MIXED CROP PRODUCTION AND RUMINANTS

ALFISOLS WITH MIXED IRRIGATED INTENSIVE CEREAL PRODUCTION AND LIVESTOCK WITH HIGH NUTRIENT APPLICATION RATES

ALFISOLS WITH RAINFED INTENSIVE CEREAL PRODUCTION AND LIVESTOCK WITH HIGH NUTRIENT APPLICATION RATES

ANDISOLS ON BARE LAND WITH LITTLE CROP PRODUCTION

ANDISOLS ON HILLY LAND WITH LITTLE CROP PRODUCTION

ANDISOLS ON HILLY AND MOUNTAINOUS LAND WITH SPARSE CROP PRODUCTION AND RUMINANTS

ANDISOLS ON HILLY TREE AND SHRUB LAND WITH SCATTERED CROP PRODUCTION

HISTOSOLS AND SPODOSOLS ON WET MOUNTAINOUS LAND WITH LITTLE CROP PRODUCTION

SPODOSOLS ON HILLY TREE-COVERED LAND WITH SCATTERED CROP PRODUCTION

HISTOSOLS AND SPODOSOLS WITH RAINFED MIXED CROP PRODUCTION AND LIVESTOCK INCLUDING RUMINANTS

HISTOSOLS AND SPODOSOLS IN TREE-COVERED LANDSCAPES WITH SCATTERED CROP PRODUCTION ON LARGE FIELDS

HISTOSOLS AND SPODOSOLS ON MOUNTAINOUS LAND WITH GRAZING AND INTERSPERSED FOOD PRODUCTION

HISTOSOLS AND SPODOSOLS ON HILLY TREE-COVERED LAND GRAZED AND CULTIVATED WITH HIGH NUTRIENT APPLICATION RATE

HISTOSOLS AND SPODOSOLS ON INTENSIVELY CULTIVATED LAND WITH HIGH LIVESTOCK PRODUCTION

SPODOSOLS ON INTENSIVELY CULTIVATED LAND HIGH LIVESTOCK PRODUCTION AND NUTRIENT APPLICATION RATE

OXISOLS ON HUMID TREE-COVERED LAND WITH LITTLE FOOD PRODUCTION

OXISOLS AND ULTISOLS ON HUMID TREE-COVERED LAND WITH SCATTERED CROPLAND AND LIVESTOCK

OXISOLS AND ULTISOLS ON HUMID HILLY TREE-COVERED LAND WITH AGROFORESTRY AND SOME LIVESTOCK

OXISOLS AND ULTISOLS ON HUMID TREE-COVERED LAND WITH DIVERSE SMALL FIELD PRODUCTION AND AGROFORESTRY

OXISOLS AND ULTISOLS WITH RAINFED PERENNIAL CROPS AND AGROFORESTRY AND SOME LIVESTOCK

OXISOLS AND ULTISOLS WITH MIXED GRAZING AND CROP PRODUCTION ON LARGE FIELDS

OXISOLS AND ULTISOLS WITH RAINFED PERENNIAL CROPS AND AGROFORESTRY AND HIGH NUTRIENT RATES AND LIVESTOCK

OXISOLS AND ULTISOLS ON LAND WITH HUMID RAINFED AND IRRIGATED PERENNIAL PRODUCTION AND OTHER MIXED CROPS AND LIVESTOCK

OXISOLS AND ULTISOLS ON HUMID IRRIGATED INTENSIVE PERENNIAL PRODUCTION AND OTHER MIXED CROPS AND LIVESTOCK

ULTISOLS ON HUMID TREE-COVERED LAND WITH LITTLE CROP PRODUCTION

ULTISOLS ON HUMID TREE-COVERED LAND WITH SCATTERED CROP PRODUCTION

ULTISOLS ON HUMID TREE-COVERED LAND WITH SCATTERED CROP PRODUCTION ON LARGE FIELDS

ULTISOLS ON HUMID TREE-COVERED LAND WITH DIVERSE CROP PRODUCTION

ULTISOLS ON HILLY AND MOUNTAINOUS TREE-COVERED LAND WITH DIVERSE CROP PRODUCTION AND HIGH NUTRIENT APPLICATION RATES

ULTISOLS WITH MIXED CROP AND LIVESTOCK PRODUCTION AND HIGH NUTRIENT APPLICATION RATES

ULTISOLS ON HUMID TREE-COVERED LAND WITH DIVERSE CROP PRODUCTION AND SOME LIVESTOCK

ULTISOLS WITH MIXED CROPS INCLUDING PERENNIALS AND LIVESTOCK PRODUCTION

ULTISOLS WITH INTENSIVELY CULTIVATED RAINFED AND IRRIGATED MIXED CROP AND LIVESTOCK PRODUCTION

ULTISOLS WITH INTENSIVELY CULTIVATED RAINFED AND IRRIGATED MIXED CROP AND LIVESTOCK PRODUCTION AND HIGH NUTRIENT APPLICATION RATES

About The Nature Conservancy

The Nature Conservancy is a global conservation organization dedicated to conserving the lands and waters on which all life depends. Guided by science, we create innovative, on-the-ground solutions to our world's toughest challenges so that nature and people can thrive together. We are tackling climate change, conserving lands, waters and oceans at an unprecedented scale and providing food and water sustainably. Working in 79 countries and territories, we use a collaborative approach that engages local communities, governments, the private sector, and other partners.

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Website: www.nature.org

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About SYSTEMIQ

SYSTEMIQ is a B Corp created in 2016 to drive achievement of the UN Sustainable Development Goals and the Paris Agreement by transforming markets and business models across three areas: land use, circular materials, and energy. Working with partners across sectors, SYSTEMIQ aims to unlock economic opportunities that benefit business, society and the environment. SYSTEMIQ is a global company in London, Munich, Jakarta, Amsterdam, Sao Paulo and Paris.

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