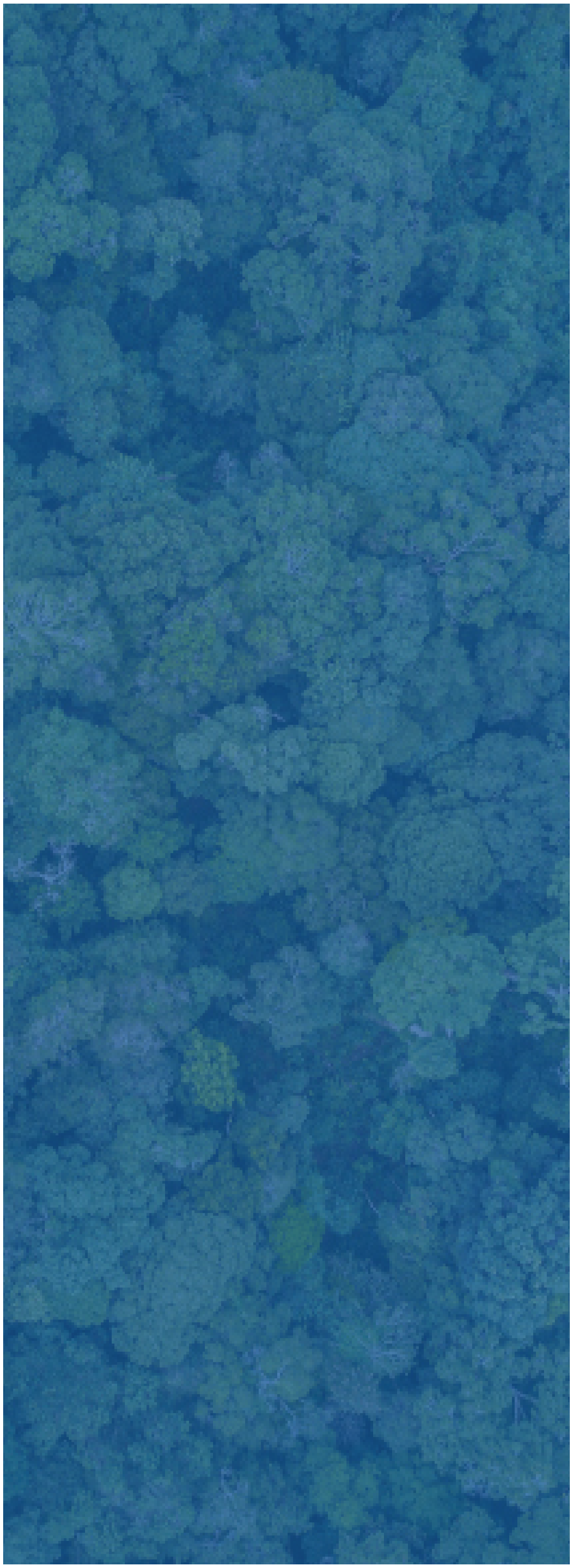
PROJECT DRAWDOWN

2025

A DRAWDOWN ROADMAP FOR FOOD, AGRICULTURE, AND LAND USE IN SOUTHEAST ASIA

Identifying the highest-priority, most effective actions for addressing climate change in the food, agriculture, and land use sector in Southeast Asia



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ASIA PHILANTHROPY CIRCLE

This work was funded by members of Asia Philanthropy Circle (APC), including Annette Akman, Quantedge Advancement Initiative, RS Group, and Watanan Petersik, with the partnership managed by APC.

Building on gaps identified by regional philanthropies, APC helped bring this project from idea to fruition, collaborating with Project Drawdown, funders, partners, and regional reviewers to shape the final product.

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We give great thanks to expert reviewers of this report.

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EXECUTIVE SUMMARY

To help avoid dangerous levels of climate change, we need to rapidly cut greenhouse gas emissions from the food, agriculture, and land use (FALU) sector. We also need to preserve natural carbon sinks, boost nature-based carbon removal, and promote food system changes that enhance both climate resilience and human well-being.

Southeast Asia is one of the most important regions in the world for climate action within the FALU sector, as this sector is responsible for more than half (54%) of greenhouse gas emissions in the region.[1] Fortunately, targeted interventions can mitigate emissions while supporting climate adaptation and offering other benefits, including improved farmer incomes and healthier ecosystems.

This report details a science-based portfolio of actions – outlining exactly what is needed, when and where, to maximize the impact of FALU greenhouse gas reduction efforts in Southeast Asia. We identify hotspots of emissions – places that have disproportionately high emissions with the greatest potential for emissions reduction per land area – and calculate the impact of interventions to reduce emissions without reducing crop yields. We synthesized findings from hundreds of data sources to distill the most impactful climate solutions in various locations. Solutions are evaluated and ranked by potential emissions savings, although the economic costs and benefits to people they provide are discussed later in the report.

Key Findings

- We identify opportunities to reduce direct emissions from FALU in Southeast Asia by 1.9 billion tons of carbon dioxide-equivalent (CO_2-eq) per year.[2]
- Interventions can result in a disproportionately large reduction in greenhouse gas emissions in certain geographic and sectoral hotspots.
- Deforestation and other land cover changes are the biggest drivers of emissions in 56% of provinces across Southeast Asia. Meanwhile, rice cultivation dominates emissions in 42% of provinces and overuse of nitrogen fertilizers leads in 2% of provinces.
- Rice production generates almost one third of regional methane emissions. Improved water management could reduce emissions by 64 million tons without reducing rice yields.
- Targeted interventions in high-priority areas can yield major emissions reductions. For example, protecting 20% of carbon-dense forests in Southeast Asia offers 83% of the carbon savings potential for forest protection across the region; 64% of emissions savings from improved rice cultivation could be achieved on 20% of rice farms; and 80% of emissions savings from improved nutrient management would come from focusing on 20% of farms using excess fertilizers.
- These climate solutions have many additional benefits, such as improved air and water quality, improved human health, and enhanced resilience to changing temperature and precipitation patterns.

1 For the purposes of this study, we define Southeast Asia as including the entire Indochinese Peninsula and Malay Archipelago (including the countries of Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, Timor-Leste, and Vietnam).
2 Greenhouse gas emissions are reported in metric tons of carbon dioxide-equivalent (CO_2-eq) emissions, using conversion values provided in the Intergovernmental Panel and Climate Change's (IPCC) Sixth Assessment Report (AR6).

COUNTRY-SPECIFIC FINDINGS

Indonesia

- Preventing deforestation in Indonesia, the region's largest country, is the biggest lever to reduce emissions.[3] Roughly 962,000 hectares of forests were destroyed in the country per year between 2001 and 2023, resulting in an average of 646 million tons of CO_2-eq annual emissions. Preventing those emissions by protecting forests would reduce national FALU emissions by 62%. Focused protection of 20% of Indonesia's forests can yield roughly 80% of these benefits.

- While deforestation and peatland degradation are the major sources of emissions throughout much of Indonesia, improving rice production in Java on 20% of the island's fields could reduce rice-related emissions by 50% without reducing rice yields.

Thailand

- Throughout much of Thailand, improving rice production is the most important lever for reducing emissions.

- Protecting 20% of Thailand's carbon-rich peatlands can reduce emissions from these ecosystems by 61%.

Vietnam

- Vietnam's rice fields – concentrated in river deltas in the north and south of the country – are often harvested two or three times per year. These rice fields are some of the highest greenhouse gas–emitting farm fields in the world. Draining flooded rice fields once or more per year – known as non-continuous flooding – can reduce emissions by 17 million tons per year without reducing yields.

- Deforestation on mineral soils is the leading driver of emissions in Vietnam. Focused protection of 20% of the country's forests would reduce deforestation-related emissions by 86%.

Philippines

- Rice production is the biggest driver of emissions in the Philippines, responsible for 20 million tons of CO_2-eq emissions per year. Targeted implementation of non-continuous flooding in rice paddies can reduce annual emissions by 6 million tons without reducing yields.

- Hotspots of excessive fertilizer use are pronounced within the Western Visayas and southern parts of the country. Improving nutrient management on 20% of croplands could reduce emissions from excessive fertilizer use by 51%.

Cambodia

- Forest loss in Cambodia generated about 68 million tons of CO_2-eq emissions. Targeted protection of 20% of forests in the country could reduce these emissions by 75%.

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3 Tree cover losses were calculated with satellite data from Hansen et al. (2013), and focused on losses from shifting agriculture and agricultural expansion rather than losses associated with wildfires, forestry, and urbanization, according to data on drivers of tree cover loss from Curtis et al. (2018).

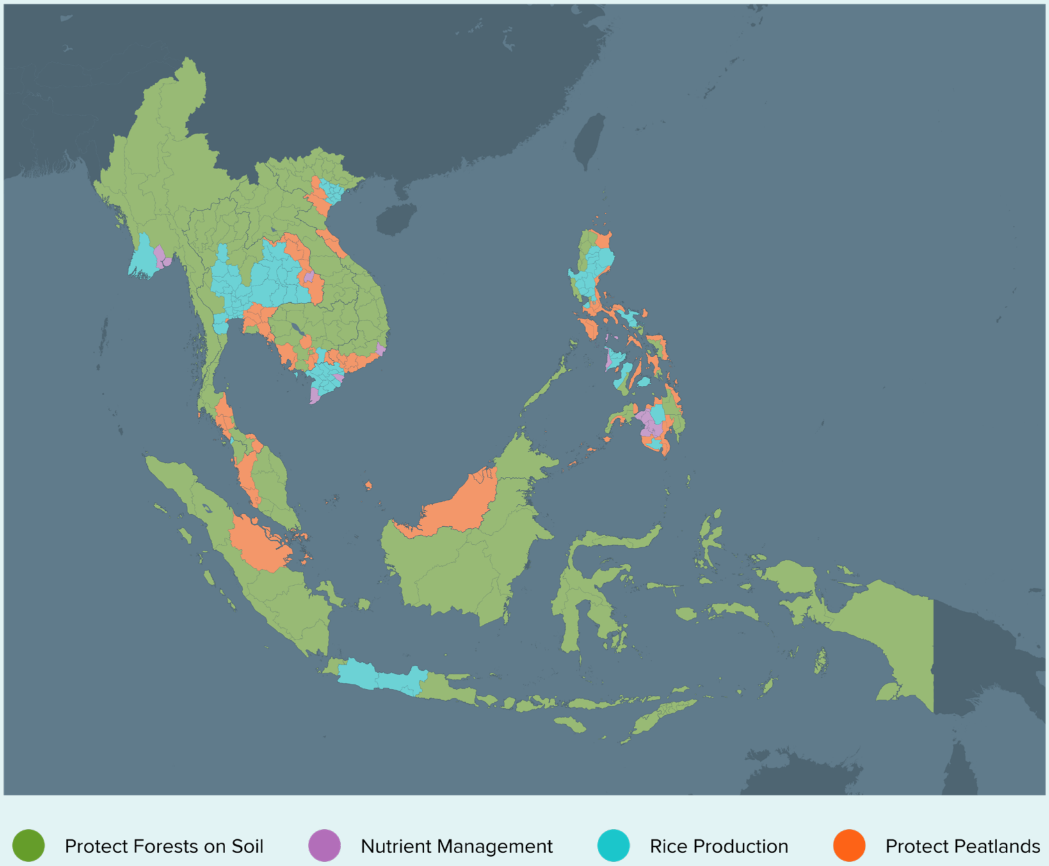


FIGURE 1. *Climate solution with the greatest overall potential to reduce greenhouse gas emissions at the province level.*

SETTING THE STAGE

Agriculture is central to Southeast Asia

Agriculture is central to Southeast Asia's economy, both in terms of gross domestic product (GDP) and employment. The agricultural sector provides 30% of jobs across the region, which exceeds the global average (Figure 2) (Beintema et al., 2012). Moreover, 31% of all land in Southeast Asia is used for agriculture, according to U.N. Food and Agriculture Organization FAOSTAT land data from 2022.

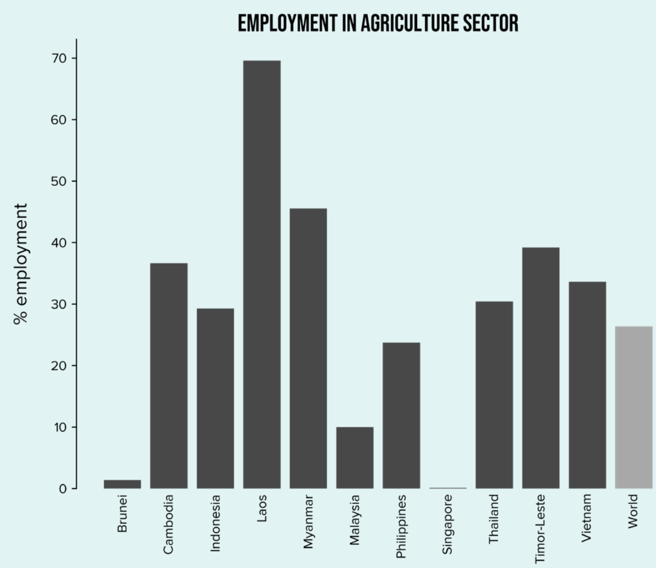
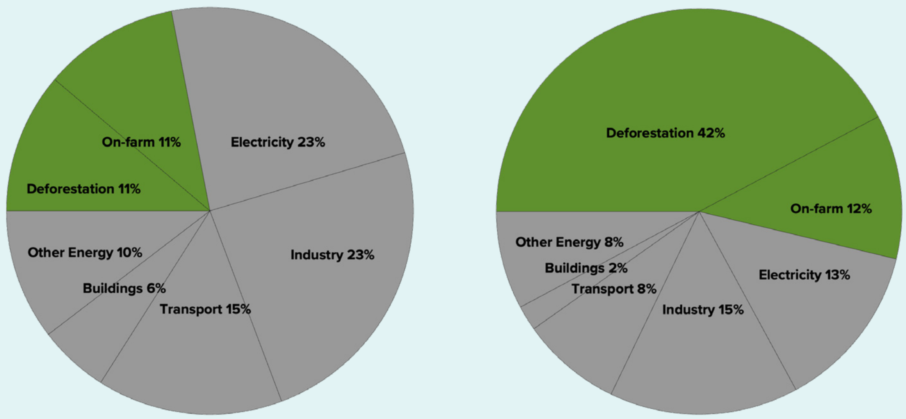


FIGURE 2. *Employment in the agriculture sector (% of total) in 2022. Data source: World Bank.*

Overview of emissions

Just as FALU has a disproportionate impact on the economies of Southeast Asia, the sector has an outsized impact on the region's greenhouse gas emissions as well. In total, FALU is responsible for 2.2 billion tons of CO_2-eq greenhouse gas emissions across Southeast Asia, which represents 54% of all emissions from the region, compared to the global average of 22% (Figure 4). In Southeast Asia, these emissions are generated largely by deforestation.

The regional breakdown of emissions contrasts sharply with global emissions. Emissions from Southeast Asia's transport, industry, and electricity sectors are approximately half of global averages, for example, while emissions from deforestation and other land use changes are four times the global average.



FIGURES 3 & 4. *Sectoral breakdown of greenhouse gas emissions globally (left) and in Southeast Asia (right). Data source for year 2019: IPCC AR6 and underlying sources.*

The dominant source of emissions in Southeast Asia stems from land use change, which includes the categories in Table 1 below. Emissions per hectare reflect carbon lost to the atmosphere both above and below ground.

These land use changes are almost always executed for agricultural expansion, tree plantations for timber, or aquaculture. Every hectare of peatland lost in the region emits, on average, 2,010 tons of CO_2, whereas every hectare of mangrove lost emits roughly 800 tons of CO_2.

TABLE 1. *Land use change type and corresponding GHG emissions*

Land use change type	Soil type	GHG emissions per hectare in Southeast Asia
Deforestation on mineral soils	Mineral soils are formed from the weathering of rocks – as opposed to wetter soils that are formed from organic matter and sediment in waterlogged conditions	~650 tons CO_2-eq
Deforestation of mangroves	Waterlogged soils in coastal environments, which may contain carbon-rich peat	~800 tons CO_2-eq
Deforestation and draining of peatlands	Soils are formed from carbon-rich, dead and decaying plant material under waterlogged conditions	~2,010 tons CO_2-eq

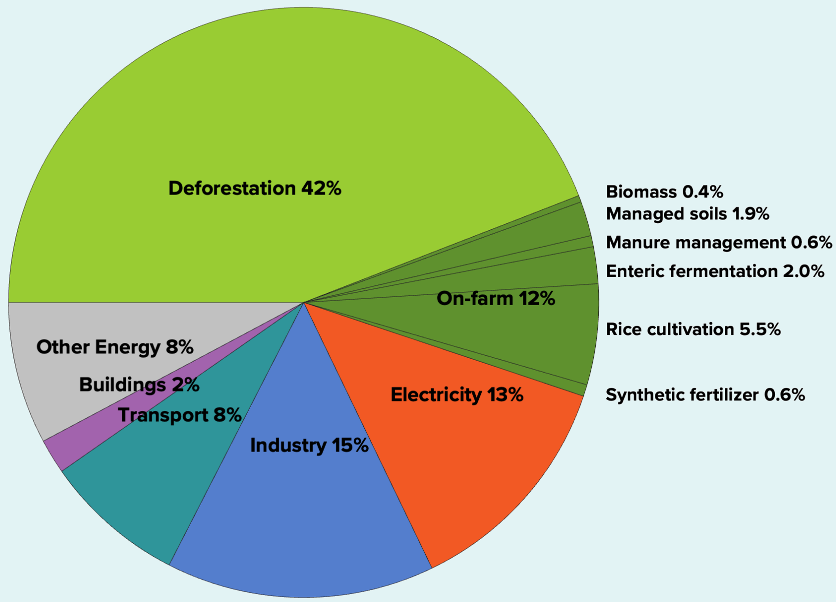


FIGURE 5. *Sectoral emissions breakdown. Data sources: Minx et al. (2021), EDGAR database, IPCC WGIII AR6.*

Southeast Asia – a natural focus for mitigation action

Southeast Asia is well-positioned to serve as a proving ground for the implementation of a wide range of climate solutions in the FALU sector for several reasons:

- FALU emissions are more dominant in Southeast Asia than in any other region in the world.
- Differences in emission source types across geographies within the region create hotspots for targeting interventions.
- Trends in land use and demographics suggest that Southeast Asia will become even more important for global emissions in the near future.

Hotspots

Hotspots have disproportionately high emissions for a given land area. In this analysis, we highlight these hotspots to see if they have the greatest potential for emissions reduction. Hotspots have the potential to follow "80:20 rules," in which we could expect to get roughly 80% of the benefits – in this case, emissions reductions – by focusing on 20% of the area (West et al., 2014). Targeted interventions in these hotspots can give us the "biggest bang for the buck" in addressing climate change.

Trends

Southeast Asia currently contains 8.5% of the global population (or 695 million people), and is projected to increase to 774 million people by 2050, approximately scaling with global population growth, according to U.N. population projection data. While overall per capita greenhouse gas emissions are relatively low in Southeast Asia, per capita FALU emissions in the region are above the global average and could rise above those of high-income countries given current trends, according to World Bank data. There is a trend in Southeast Asia toward greater caloric consumption with an increase in calories from animal products (Figure 6). Southeast Asia's total calorie supply is approximately four-fifths of that of Europe, with consumption of animal products approximately one third that of Europe.

If Southeast Asia catches up with European consumption of animal products while maintaining consumption of greenhouse gas–intensive rice at a rate 2.3 times that of the global average, per-person emissions associated with farming would be among the highest in the world, according to U.N. Food and Agriculture Organization food balance sheets.

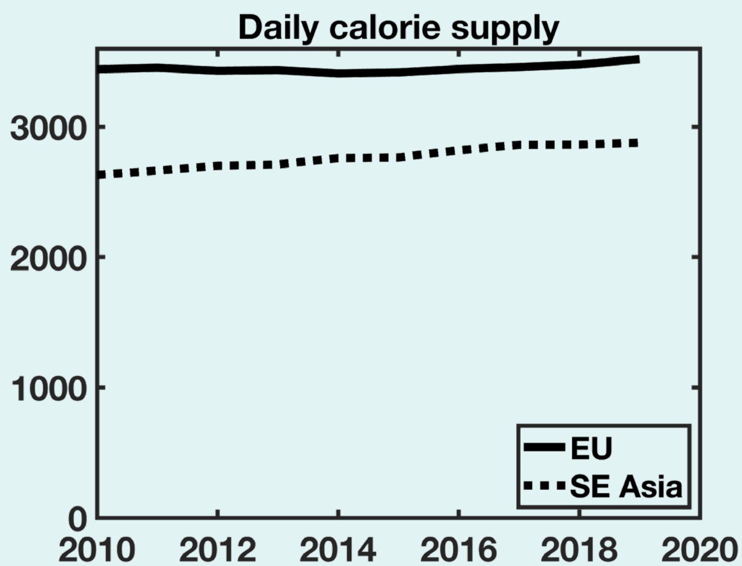


FIGURE 6. *Daily calorie supply in Southeast Asia (dotted line) and European Union (solid line). Data source: FAO Food Balance Sheets, downloaded Sep 4, 2024.*

Climate interdependency

Southeast Asia is considered to be at greater risk of economic losses from climate change than other regions of the world (Raitzer et al., 2015). If climate change isn't addressed, these economic impacts will come in a variety of forms. By 2050, countries in the region are at risk of losing more than 35% of their gross domestic product (GDP) due to climate change and natural hazards, with repercussions for agriculture and other key sectors (Renaud et al., 2021).

Impacts particularly salient in Southeast Asia include:

- Changing weather patterns are leading farmers to modify long-standing cropping calendars, which can lead to decreased yields due to high temperatures during sensitive phenological stages (Reed, Mendelsohn & Abidoye, 2017; Shrestha et al., 2018; Naresh Kumar et al., 2014).
- Increased temperatures make fieldwork more difficult, exacerbating the impacts of climate change on crops (De Lima et al., 2021).
- Droughts can lead to out-of-control fires in both forests and peatland, polluting the air.

With judicious interventions, responses to climate change can be implemented in a way that improves outcomes for people and the planet. Mitigating climate change can also provide positive economic returns by reducing the toll of climate change's impacts across the region. A report by the Asia Development Bank found that investments in emissions reduction make financial sense given the region's vulnerability to climate change (Raitzer et al., 2015).

Importance of co-benefits to the region

Climate change mitigation actions in the FALU sector have many additional benefits, including improved air quality and heightened resilience to extreme weather, according to the IPCC AR6 (Sixth Assessment Report) Working Group III Summary for Policymakers. These mitigation actions can also improve yields and farmer incomes, which comprise a major part of regional GDP.

The health benefits of some mitigation actions – such as finding alternatives to burning rice straw and reducing fires on peatland – are particularly important in Southeast Asia, given the recurring air quality issues that residue burning and peatland fires generate (Vadrevu, Ohara & Justice, 2018).

Another benefit of well-designed climate mitigation in the FALU sector is the protection of Southeast Asia's natural ecosystems. Natural ecosystems can be protected directly by supporting the establishment of protected areas (PAs), or through forest-, peatland-, or mangrove restoration programs. Natural ecosystems can also be protected indirectly, through reduced demand for agricultural products by shifting diets and limiting food waste. Changing agricultural practices – by preventing nutrient overuse that harms aquatic and other ecosystems, for example – can also help safeguard natural ecosystems.

Looking ahead

Southeast Asia is in a position to address FALU emissions in a way that enhances climate resilience, improves farmer livelihoods, and strengthens environmental sustainability. While the FALU sector constitutes a very significant part of the landscape and economy of Southeast Asia, the top opportunities for impactful interventions are concentrated in a small number of sources and geographies. By calling attention to these interventions, we aim to guide climate investment and action to maximize impact.

LEVERAGE POINTS FOR CLIMATE MITIGATION IN SOUTHEAST ASIA

Key Findings

- Protecting forests is the largest lever to reduce emissions in Southeast Asia.
- Dominant sources of emissions differ at the subnational level, indicating a need for differing solutions in different regions.
    - Within the land use sector, protecting forests has the most potential to reduce emissions in 76% of provinces across Southeast Asia, rice cultivation has the most potential in 23% of provinces, and fertilization has the most potential in 1.4% of provinces.
- The greatest per-hectare opportunities for impactful climate mitigation are the protection of peatlands (2,010 tons CO_2-eq/ha/yr) and mangroves (approximately 800 tons CO_2-eq/ha/yr), followed by forests on mineral soils (650 tons CO_2-eq/ha/yr).
- The majority of deforestation occurs in a small number of hotspots, with new ones emerging in Laos, Cambodia, Malaysia, and Indonesia.
- Focused protection of 20% of forested areas on mineral soils could reduce related emissions by 83%.
- Opportunities for improved rice production are also geographically concentrated, with 20% of rice-growing areas representing 64% of solution potential.
- Reducing food loss and waste (FLW) can provide substantial mitigation benefits, along with keeping ruminant meat consumption low, and can complement forest protection by reducing pressures on natural lands.

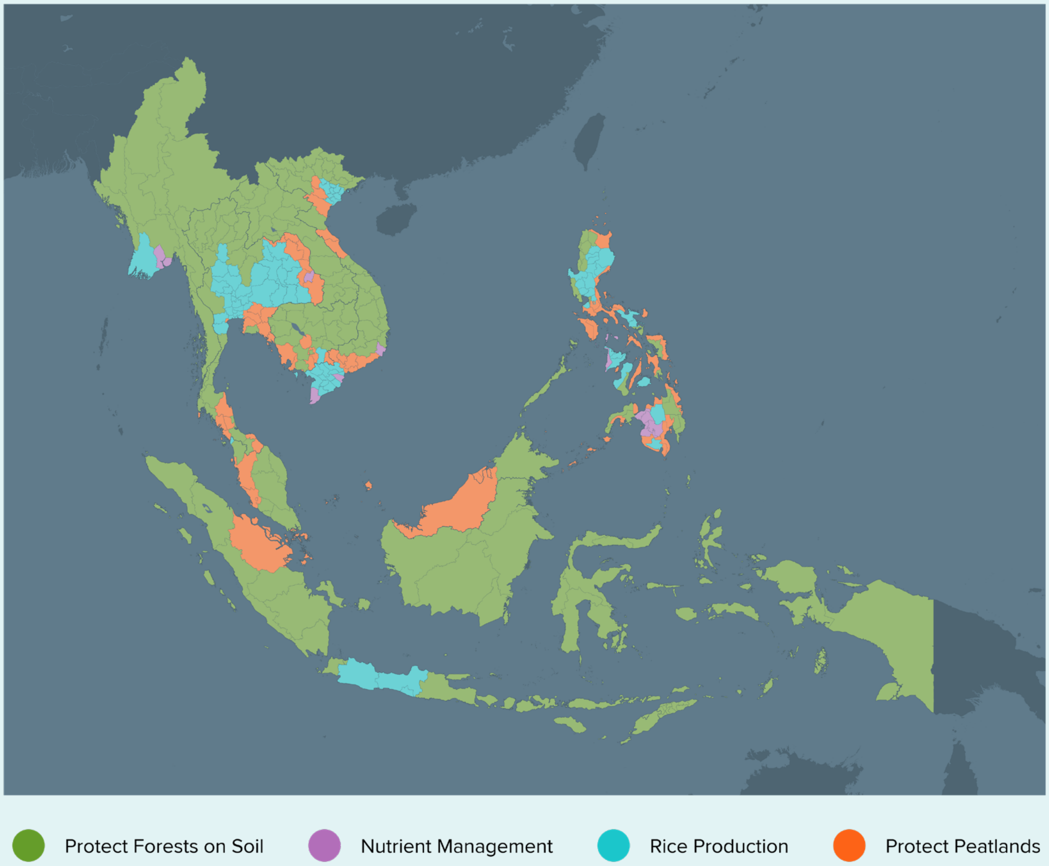


Figure 7. *The climate solutions with the greatest potential for emissions reduction at the province level.*

OVERVIEW

In this report, we provide a quantitative comparative analysis of opportunities for addressing climate-warming emissions in Southeast Asia. We combined recently developed datasets on emissions from FALU to calculate the most impactful solutions across Southeast Asia. In the main text of the report, we focus on high-level results and include detailed tables, charts, and maps in topical chapters.

Across Southeast Asia, opportunities exist to reduce direct emissions from food, agriculture, and land use by 1.9 billion tons of CO_2-eq per year. These emissions include those stemming from deforestation, drainage and land use change of peatlands, loss of mangroves, rice cultivation, nitrogen fertilizer use, and rice straw burning.

We map these emissions, as well as their reduction potential. Further emissions reductions from dietary shifts and limiting food waste also occur within the region, but often overlap with other emissions categories. For example, deforestation to facilitate oil palm or soybean production can be decreased by reducing demand for agricultural products by way of reducing food waste and shifting diets away from land-intensive foods such as beef and other ruminant meat.

Utilizing sophisticated geospatial modeling tools – which are being released as part of the new Drawdown Explorer platform – we use the latest data and algorithms to identify geographic hotspots of emissions and key regions for strategic investment. These hotspots inform the key leverage points, with the greatest potential to meaningfully address climate change, at the largest scale, at the lowest costs, and in the shortest amount of time.

For results presented in the report, we look at deforestation at a high level and differentiate between deforestation on mineral soils, deforestation on peatland, and the loss of mangroves. However, deforestation in different land use types is often combined within maps and charts, unless otherwise noted. While the outcomes of protection of these three different forest ecosystems can be very different, the general nature of the solution – protection of carbon-rich land – is similar. We provide quantitative differentiation of solutions and emissions associated with these three forest ecosystems within the text. Changing diets and reducing FLW are very important solutions, but do not have a spatial component; consequently, those solutions are not included in the spatial maps presented.

ACROSS SOUTHEAST ASIA, OPPORTUNITIES EXIST TO REDUCE DIRECT EMISSIONS FROM FOOD, AGRICULTURE, AND LAND USE BY 1.9 BILLION TONS OF CO_2-EQ PER YEAR.

COMPARING EMISSIONS ACROSS SOURCES

As a first step towards a comparative analysis, we examine emissions across sources and countries. The results are shown in Figure 8. We include non–land use emissions to highlight the importance of the land use sector in Southeast Asia, but do not analyze those emissions.

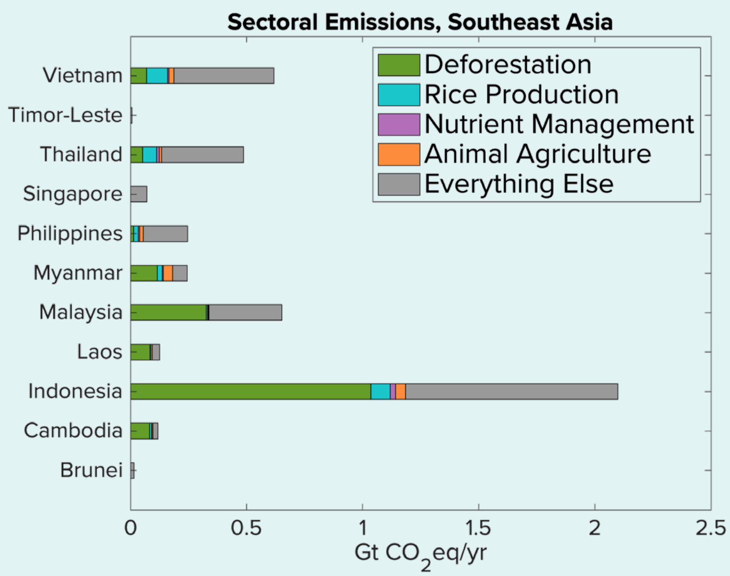


FIGURE 8. *Sectoral emissions in 11 Southeast Asian countries. "Everything else" includes all non-land sector emissions, such as transportation, electricity production, and industrial emissions. Due to temporal discrepancies in data availability and mismatches between subsectors in data sources, the sum of emissions presented here will not equal the data presented in summary chapters. In this figure, deforestation encompasses all tree cover loss and land use change.*

National-level deforestation emissions in Figure 8 encompass those from deforestation on mineral soils and on peatlands and mangroves. The category also includes carbon emitted into the air from the soil in these ecosystems, which is discussed further in the topical chapters.

Rice production and livestock production – which both generate methane – are the next largest drivers of emissions in the region. Ruminant animals, such as cattle, goats, and buffalo, produce methane in their digestion through a process called enteric fermentation. In subsequent maps, we discuss how emissions can be reduced from rice production; potential emissions savings from livestock are not mapped but are discussed in the context of diet-related emissions.

Deforestation

Forests dominate the Southeast Asian landscape. The region is home to nearly 15% of the world's tropical forests but has some of the world's highest rates of deforestation (Estoque et al., 2019).

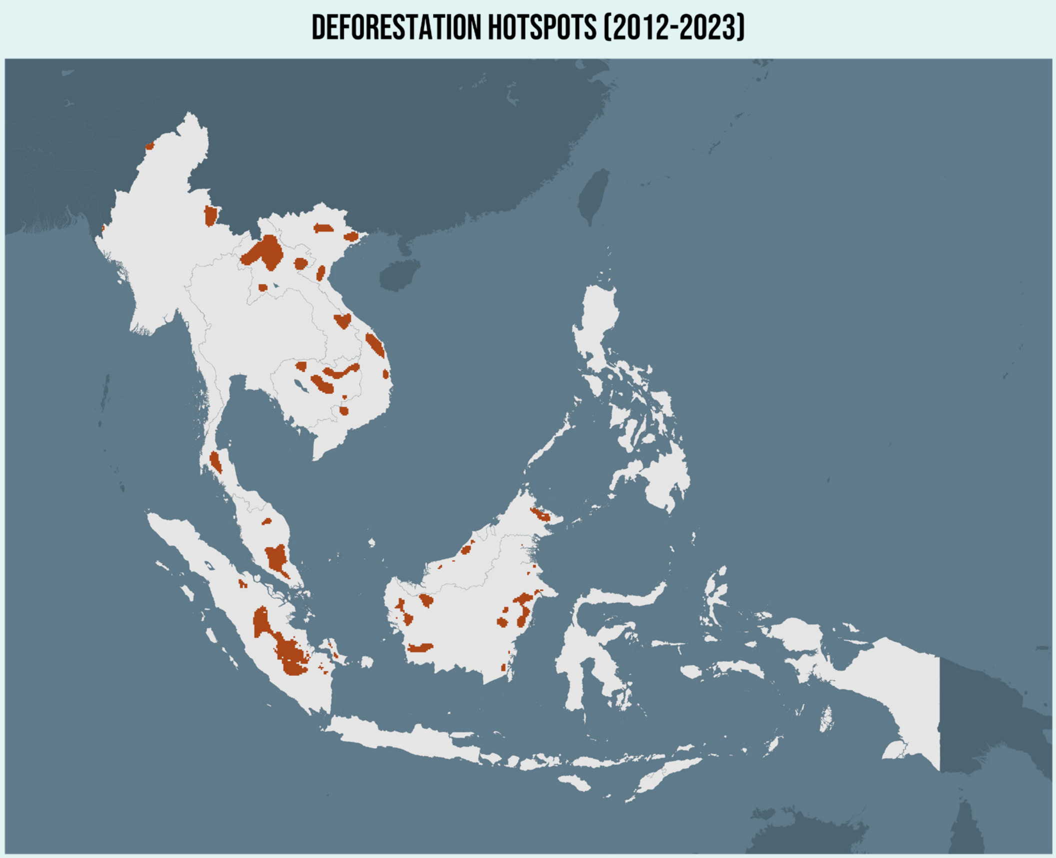


FIGURE 9. *Hotspots of deforestation (on peatlands, mangroves, and mineral soils) during the period from 2012 to 2023.*

Between 2001 and 2023, Southeast Asia lost about 1.8 million hectares of forest per year – an annual rate of about 0.7%. This deforestation resulted in 1.2 billion tons of CO_2-eq emissions per year. This is the largest source of emissions in Southeast Asia, and protecting these forests is the largest lever to reduce emissions.

Tropical rainforests on mineral soils are big stores of carbon, containing about 650 metric tons of carbon dioxide per hectare – the equivalent emissions of 10 cars over their lifetimes. We distinguish forests on mineral soils (formed from the weathering of rocks) from those on wetter organic soils (found in peatlands) because the soils of peatland and mangrove areas contain more organic matter and carbon than mineral soils.

Today, a growing and increasingly affluent population – combined with booming global demand for exports such as oil palm, timber, and rubber – is placing significant pressure on the region's forests.

Using the latest remote-sensing data on forest change, we identify hotspots of emissions from deforestation within Southeast Asia. We define hotspots (shown in Figure 9) as locations that lost at least 25% of forests between 2012 and 2023 and were at least 50% forested in 2012.

Between 2012 and 2023, hotspots of deforestation in the region were in Laos, Cambodia, Malaysia, and Indonesia. Within Indonesia, eastern Kalimantan and central Sumatra experienced significant losses. Loss of forests in these hotspots is driven almost exclusively by land clearing for commodity agriculture in Indonesia and Malaysia, while a mixture of drivers – including commodities, shifting agriculture, and plantation harvesting – contributed to deforestation in Cambodia and Laos. Details of methods and emissions fluxes are provided in the deforestation topical chapter.

BETWEEN 2001 AND 2023, SOUTHEAST ASIA LOST ABOUT 1.8 MILLION HECTARES OF FOREST PER YEAR – AN ANNUAL RATE OF ABOUT 0.7%.

Peatlands

Peatlands are diverse ecosystems characterized by waterlogged, carbon-rich peat soils consisting of partially decomposed plant material. Southeast Asia's coastal lowland areas are home to some of the most pristine forested peatlands.

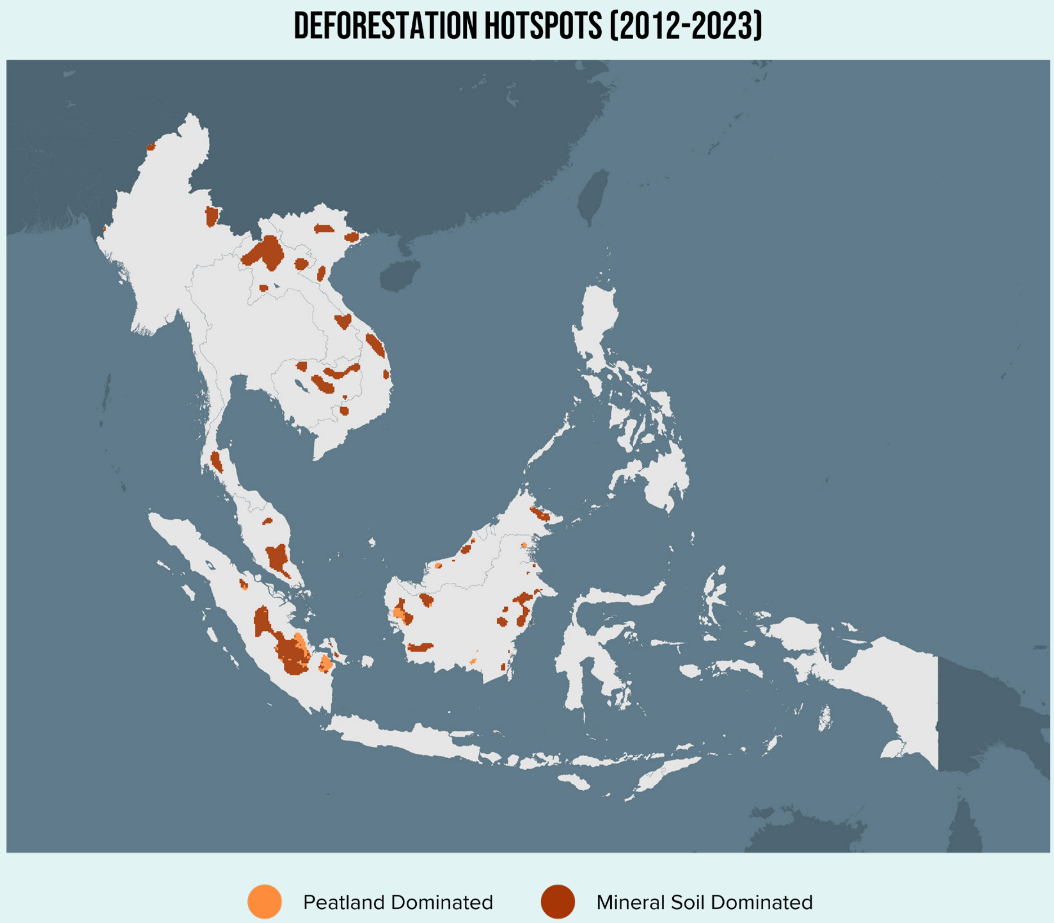


FIGURE 10. *Hotspots of deforestation on mineral soils (red) and peatland (orange) in the period from 2012 to 2023. Hotspots are identified as regions that were at least 50% forested in 2012, with loss of at least 25% of that forest.*

Peatlands are degraded or destroyed through the clearing of vegetation and drainage for agriculture, forestry, peat extraction, or other development. Drainage exposes carbon-dense soils to oxygen and generates disproportionately large and sustained greenhouse gas emissions. Removal of overlying vegetation produces additional emissions while also slowing or stopping the rate of carbon uptake. Land use change of peatlands in Southeast Asia emits three times the carbon, per hectare, of tropical forests on mineral soils.

Peatland emissions may exceed those from deforestation over long timescales, and draining is linked to amplified fire risk, land subsidence, and regionally altered hydrology (Carlson et al., 2017; Frolking et al., 2011).

In Southeast Asia, these important wetlands are under threat due to agricultural expansion and demand for oil palm, rubber, timber, and soy. The majority of peat swamp forests in Southeast Asia are converted for oil palm and tree plantations, as well as aquaculture and urban development (Sasmito et al., 2025).

Between 2001 to 2023, the deforestation and draining of peatlands in Southeast Asia emitted on average 577 million tons of CO_2-eq each year. Emissions from peatland conversion are highly concentrated (Figure 10). Protecting 287,000 hectares of peatlands per year could prevent the emission of these 577 million tons of CO_2-eq each year – which is approximately half the emissions reduction potential of protecting 1.8 million hectares of forests on mineral soils.

For this analysis, when a hectare of peatland is deforested and drained, all of the carbon in the above-ground biomass ends up in the atmosphere, in addition to 30 years of emissions of carbon from the soil (known as committed emissions). We found that protecting peatlands has the highest potential emissions savings per hectare – every hectare conserved could save 2,010 tons CO_2-eq emissions. For more information on methodology, see the topical chapter on peatlands.

Mangroves

Mangroves are unique ecosystems that fringe the coastlines of Indonesia, Malaysia, Myanmar, the Philippines, Thailand, and Vietnam. Mangroves are highly productive ecosystems that sequester carbon via photosynthesis, storing it primarily below ground in sediments where waterlogged, low-oxygen conditions help preserve it (Adame et al., 2024; Lovelock et al., 2017). These ecosystems are also efficient at trapping carbon suspended in water, which can comprise up to 50% of carbon sequestration (McLeod et al., 2011; Temmink et al., 2022). Mangroves operate as large carbon sinks, with long-term carbon accumulation rates averaging 5.1–8.3 tons CO_2-eq per hectare annually (McLeod et al., 2011).

Between 2001 and 2023, roughly 29,000 hectares of mangroves were lost across Southeast Asia each year, generating 23 million tons of CO_2-eq annually. Mangrove loss was highest in Indonesia, which is home to the majority of the region's mangroves. Malaysia, Myanmar, and Thailand also had losses that generated more than 1 million tons of CO_2-eq per year.

Deforestation of mangroves for agriculture and aquaculture (such as rice fields and shrimp ponds), removes biomass and impacts sediment carbon stocks (Chauhan et al., 2017; Sasmito et al., 2019). For mangrove conversion, we assume all of the biomass is lost to the atmosphere and half of the carbon stored in the soil is emitted.[4]

4 Similar to methods in Sasmito et al. (2020)

DIRECT SOLUTIONS

Forest Protection

One of the direct solutions to addressing deforestation and land use change is legal protection. Protected areas and Indigenous peoples' lands reduce – but do not eliminate – forest clearing relative to unprotected areas (Li et al., 2024; Sze et al., 2022; Wolf et al., 2021; Wade et al., 2020). For the most part in this report, we provide estimates of emissions reductions from perfect protection, but we also provide emissions estimates for more realistic protection, based on recent best estimates of PA effectiveness.

Globally, Wolf et al. (2021) found that rates of forest loss inside protected areas are 40.5% lower on average than in unprotected areas. Regional studies find similar average effects of protected areas on deforestation rates. During the 21st century to date, forest protection measures in Southeast Asia have been, on average, about 29% effective at conserving forests, based on the forest-area-weighted average of the reported effectiveness in Wolf et al.

Market-based strategies and other policies can complement legal protections by increasing the value of intact forests and reducing incentives for clearing (Garett et al., 2019; Lambin et al., 2018; Levy et al., 2023; West et al., 2023). The estimates in this report are based on legal protection alone because the effectiveness of market-based strategies is difficult to quantify. However, strategies such as sustainable commodities programs, reducing or redirecting agricultural subsidies, and strategic infrastructure can also aid in protection.

Formally recognizing Indigenous lands, both in Southeast Asia and elsewhere, is a critical component of forest protection (Jones et al., 2018; Meng et al., 2023; Watson et al., 2014).

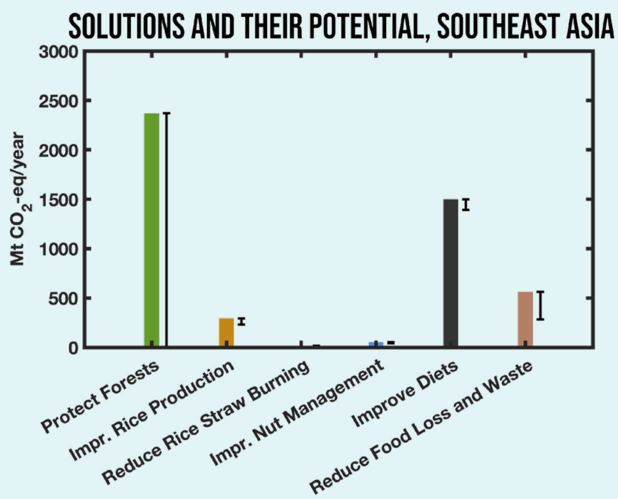


Figure 11. Cross-sectoral emissions and a range of solutions are shown. Solid color bars represent the total emissions in each sector. The black vertical lines represent the range of emissions considered avoidable. Rice management, for example, has limited avoidable emissions because elements of improved rice cultivation (such as non-continuous flooding) already have some uptake across Southeast Asia. Reducing food loss and waste is represented as having the potential to reduce half of emissions, following Zhu et al. (2023).

Improve Rice Production

One of every four grains of rice eaten in the world is grown in Southeast Asia. Indonesia, Vietnam, and Thailand are the three top rice-producing countries in the region. Most rice production takes place in flooded fields called paddies, where anaerobic conditions trigger methane production.

HOTSPOTS FOR IMPROVING RICE PRODUCTION

FIGURE 16. *Hotspots of potential emissions reduction from rice cultivation.*

Rice production in Southeast Asia generates about 293 million tons of CO_2-eq emissions annually. These emissions are mostly in the form of methane, a powerful, short-lived greenhouse gas that warms the climate 30 times more than carbon dioxide over 100 years. Rice production emits almost one third (32%) of regional methane emissions.

Two related practices reduce emissions from paddy rice production: non-continuous flooding and nutrient management. Non-continuous flooding is a water management technique that reduces the amount of time that rice paddy soils spend under fully saturated conditions, thereby reducing methane.

Non-continuous flooding can include alternate wetting and drying (AWD), which allows water to subside naturally through evaporation and infiltration, leaving the soil dry for several days before re-flooding. It can also include mid-season drainage, in which rice fields are drained for about seven days in the later part of the growing season (Searchinger et al., 2019). Draining a rice field once or more per year can dramatically reduce methane emissions without reducing rice yields.

Unfortunately, non-continuous flooding increases nitrous oxide emissions. Nutrient management helps to address this challenge by controlling the timing, amount, and type of fertilization to maximize plant uptake and minimize nitrous oxide emissions.

Hotspots of potential for implementing improved rice cultivation (Figure 16) show that non-continuous flooding and nutrient management on 20% of the region's rice-growing areas can tackle 64% of addressable emissions.

Approximately 14% of the flooded rice area in Southeast Asia is managed with non-continuous flooding. The potential area for adopting the practice without reducing yields is 81%. Non-continuous flooding and nutrient management practices on 64% of the region's rice farms could reduce emissions by 64 million tons CO_2-eq, without reducing yields. This represents a 22% reduction of rice field emissions.

Vietnam has the highest emissions per-hectare of rice field – 14 tons CO_2-eq per hectare, which is twice the regional average (seven tons CO_2-eq per hectare). The primary rice-growing areas in Vietnam are the Red River delta in the north and the Mekong River delta in the south. Continuous flooding and triple cropping of rice fields in these deltas drive 10% of global rice methane emissions, yet Vietnam produces just 5% of global rice. In this analysis, we find that improving rice cultivation on 20% of Vietnam's fields, without reducing yields, would cut emissions by 60%.

In Indonesia, Java's rice fields produce a majority of the country's crop and are a hotspot of methane emissions. Within the Barat, Tengah, and Timur provinces of Java, improved water management, using non-continuous flooding, can reduce annual emissions by about 4 million tons CO_2-eq, without reducing yields (Figure 17).

See the topical chapter on Improve Rice Production for a more detailed description of rice emissions and solutions.

DRAINING A RICE FIELD ONCE OR MORE PER YEAR CAN DRAMATICALLY REDUCE METHANE EMISSIONS WITHOUT REDUCING RICE YIELDS.

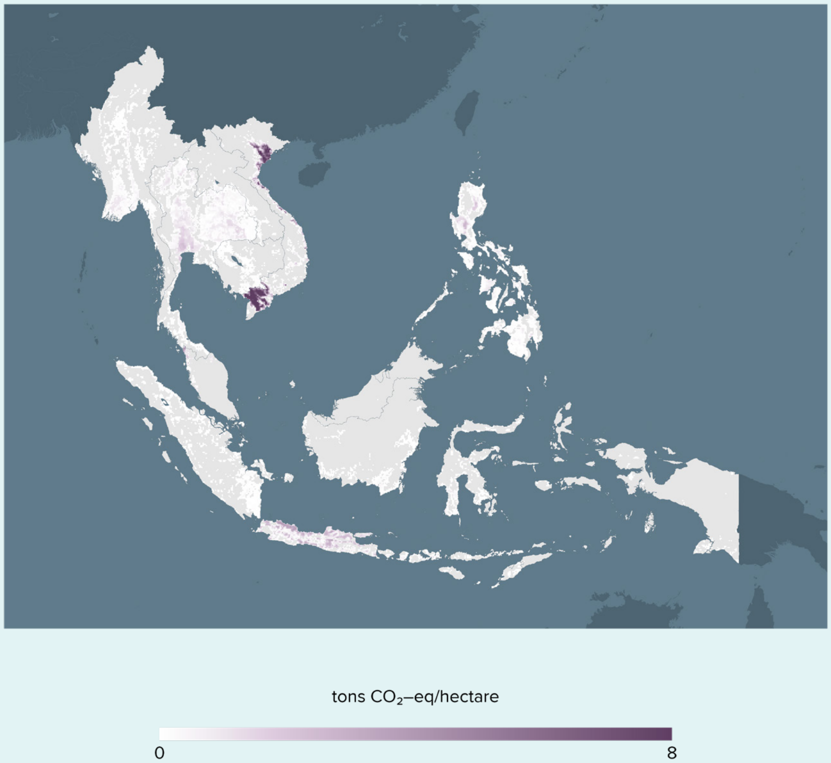


FIGURE 17. *Feasibility and emissions reduction potential from implementing non-continuous flooding, as measured in tons of CO_2-eq saved. Although it is possible to implement non-continuous flooding in all rice areas (white), it is critical to know how much emissions can be reduced where it can be adopted without reducing yields (purple). Data source: Bo et al. (2022).*

Improve Nutrient Management

Improving nutrient management involves reducing excessive nitrogen fertilizer use on croplands. Nitrogen is critical for crop production and is added to croplands through the use of fertilizers and through microbial activity. However, too much nitrogen is used in some farm fields in Southeast Asia. Some of the excess nitrogen that cannot be used quickly enough by crops is emitted to the atmosphere as nitrous oxide, a potent greenhouse gas. Using the right amount and right type of nutrients at the right time and right place can reduce nitrous oxide emissions by ensuring that the nitrogen gets taken up by crops instead of being emitted as nitrous oxide.

Across all non-rice farm fields in Southeast Asia, excess nitrogen fertilizers lead to 53 million tons of CO_2-eq emissions per year. This excess application occurs on 88 million hectares of land. Hotspots of emissions from nutrient management were focused in Thailand, Indonesia, and Vietnam (Figure 18).

We find that curtailing fertilizer applications to ensure they are used at the right time and place could reduce nitrous oxide emissions by 11 million tons, without compromising crop yields. Focusing nutrient management on 20% of cropland area could yield 80% of the emissions savings potential. See the topical chapter on Improve Nutrient Management for a more detailed description of emissions and solutions.

HOTSPOTS FOR NUTRIENT MANAGEMENT

FIGURE 18. *Hotspots of nutrient management solutions.*

INDIRECT SOLUTIONS

Shift Diets

Demand for agricultural products drives forest loss, and some of the biggest solutions within the FALU sector involve reducing that demand. One way of doing this is to shift diets.

As incomes rise, people tend to buy more meat and dairy. Meat – especially beef and lamb – has a much higher carbon footprint than protein-rich legumes and grains. For example, producing a kilogram of beef emits 33 times the amount of greenhouse gases compared to protein-rich plant-based foods, such as beans, nuts, and lentils (Poore & Nemecek, 2018). Beef can also be replaced with any other non-ruminant meat (such as poultry, pork, and fish) to generate emissions savings. Substituting ruminant meat with any other kind of meat also significantly reduces emissions.

In 2019, an international team of scientists known as the Eat-Lancet Commission developed benchmarks for a healthy, sustainable diet based on peer-reviewed information on human health and environmental sustainability (Willett et al., 2019). The commission estimated that red meat (beef, lamb, and pork) should be limited to 98 grams (210 calories) of red meat per week, which translates to 5.1 kilograms per year. Limiting beef and other ruminant meat consumption to 98 grams per person per week has health benefits and is a major lever to reduce emissions (Figure 12).

PRODUCING A KILOGRAM OF BEEF EMITS 33 TIMES THE AMOUNT OF GREENHOUSE GASES COMPARED TO PROTEIN-RICH PLANT-BASED FOODS, SUCH AS BEANS, NUTS, AND LENTILS

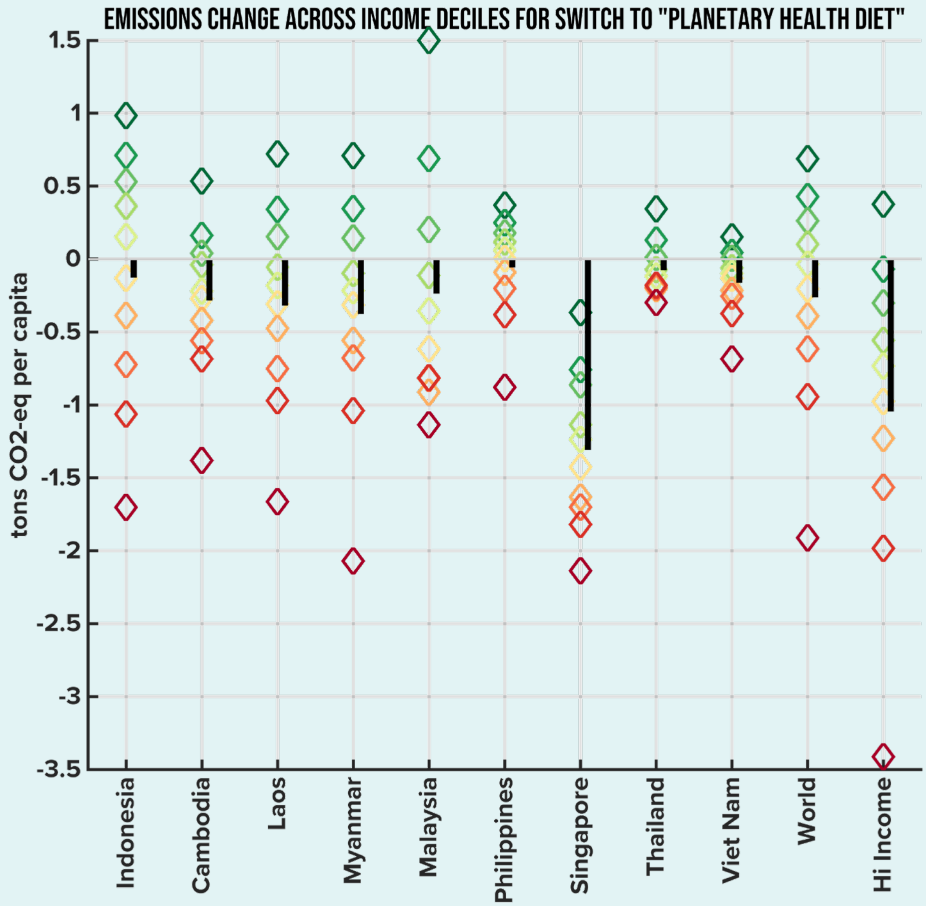


FIGURE 12. *Emissions change associated with a switch to the EAT-Lancet planetary health diet for each population income decile in each country of Southeast Asia, with world and high-income aggregate regions shown for comparison. Lower income deciles are on the top of the figure, while richer income deciles are on the bottom. The points above the x-axis represent population deciles whose meat consumption is below the planetary health diet recommendation, and shifting to this diet would result in increased greenhouse gas emissions. Points below the x-axis represent population deciles who are consuming more meat than the planetary health diet recommendations and may see improved health outcomes as well as climate mitigation outcomes. The average diet for all countries is such that moving all deciles to the planetary health diet results in a decrease in greenhouse gas emissions; this shift in average diet is represented by the black lines. This data is replotted from Li et al. (2024).*

With the exception of Laos, the average consumption of beef and other ruminant meat in Southeast Asian countries is significantly below the upper threshold of 5.1 kilograms per year set by EAT-Lancet for health and sustainability. In fact, the consumption of beef and other ruminant meat in most Southeast Asian countries is below what we would expect given per capita GDP (Figure 13).

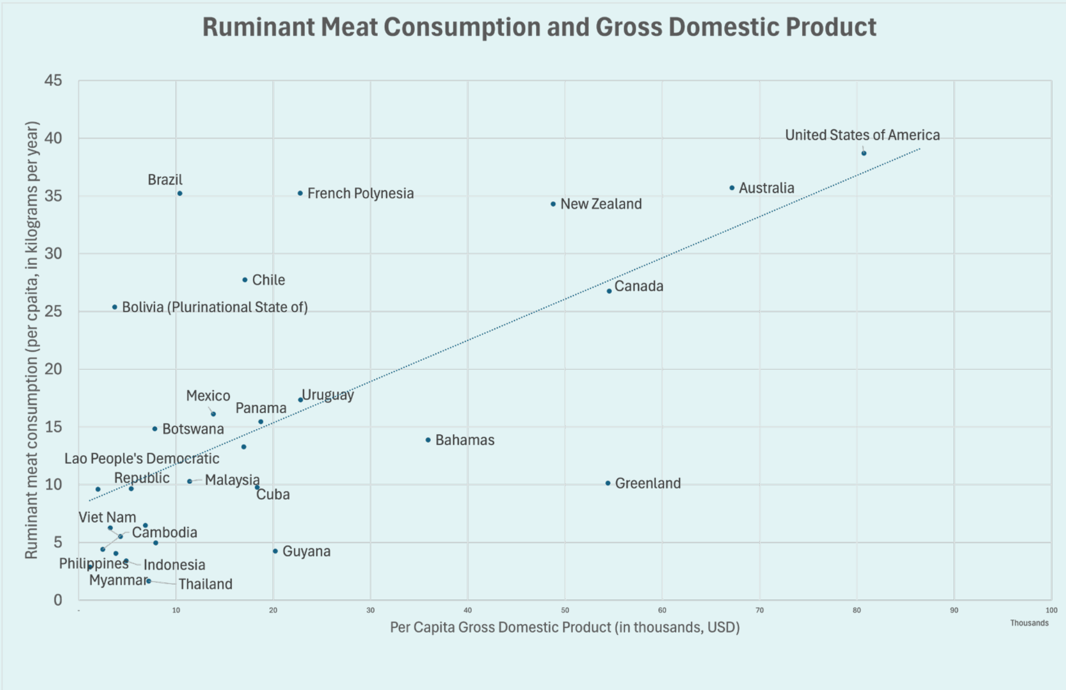


FIGURE 13. *Per capita ruminant meat consumption in kilograms per year, compared to per capita GDP. Most Southeast Asian countries are in the lower left part of the graph, indicating they have low GDP and even lower ruminant meat consumption than expected when compared to other countries with similar GDPs.*

However, we found that if everyone in Southeast Asia adopted the EAT-Lancet planetary health diet, which limits consumption of meat and dairy, emissions would be reduced by 105 million tons CO_2-eq per year.

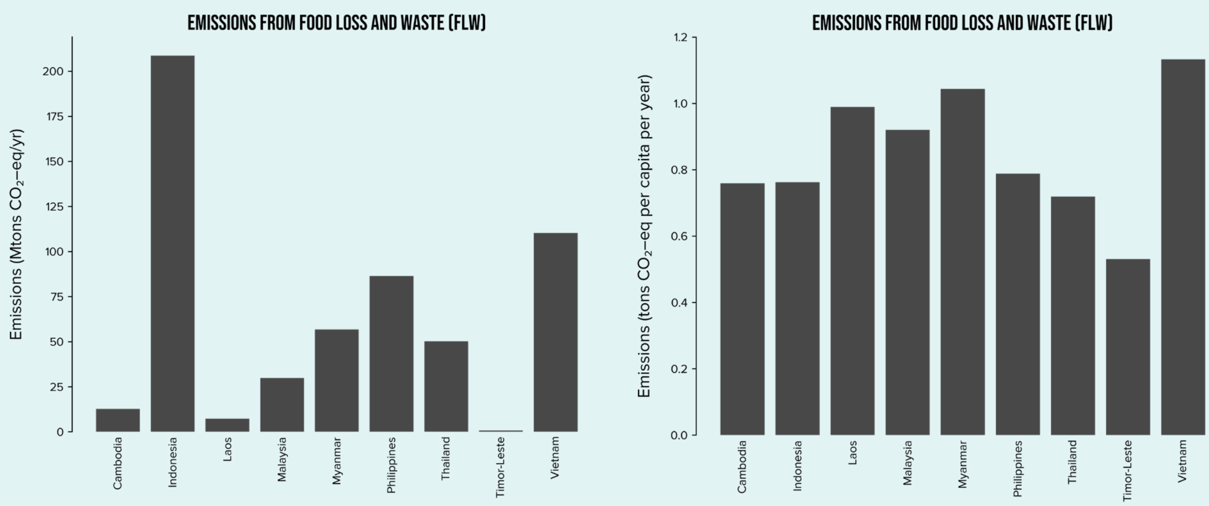
While the relative impact of dietary change as a mitigation method is smaller than other FALU solutions, if Southeast Asia approaches the consumption habits of high-income regions this may become a lever that becomes more important for climate mitigation.

Reduce Food Loss and Waste

Another method of reducing pressure to expand agricultural land is to address FLW. About one third of food by weight is lost or wasted along the global supply chain, which represents about 25% of the calories produced.

The greenhouse gases associated with FLW include gases emitted from the production and distribution of that particular food, including emissions from agriculture-related deforestation and soil management; methane emissions from livestock and rice production; and nitrous oxide emissions from fertilizer management. FLW emissions also include methane emissions from landfills after food is wasted.

Average annual emissions from food waste in Southeast Asia is 563 million tons. According to recent research, Southeast Asian countries have slightly lower per capita food waste (21% of calories) compared to the global average (25% of calories). However, between 2004 and 2014, FLW in the region increased by about 43%, largely due to increased food consumption linked to increased GDP (Gatto et al., 2024).



FIGURES 14 (LEFT) AND 15 (RIGHT): *National-level emissions (left) from food loss and waste (FLW), and per capita emissions (right) from FLW in tons CO_2-eq per capita per year. Data from Zhu et al. (2023). FLW data were unavailable for Brunei or Singapore.*

Emissions from FLW have two major sources: production (including those from fertilizers, land use change, storage, processing, and distribution) of food that is lost or wasted, and the emissions from food waste management. The impact of FLW has been quantified at national scales by Zhu et al. (2023). Although Indonesia has high total emissions from food waste (Figure 14), on a per capita basis the country's food waste is average for the region (Figure 15).

COUNTRY-SPECIFIC HOTSPOTS ACROSS SOURCES

As a complement to understanding sources with the highest emissions and solutions potential, we developed a geographic analysis of emissions across countries.

In the country-specific comparisons below, we assess solutions in Vietnam, Indonesia, the Philippines, Thailand, and Cambodia, and highlight areas of the most impactful levers for addressing emissions.

Vietnam

One third of emissions (200 million tons) in Vietnam come from food production and land use changes. Protecting forests, reducing food waste, and improving rice production are the greatest levers within the country. Vietnam's rice fields – concentrated in the river deltas in the north and south of the country – are some of the highest-emitting farm fields in the world. On the outskirts of these deltas, land use change within peatlands drives emissions as well.

Protect Forests, Peatlands, and Mangroves

In 2020, Vietnam had 14.5 million hectares of natural forest, extending over 40% of its land area. Between 2001 and 2023, forests were lost on an average of 95 thousand hectares annually, resulting in 53 million tons of carbon dioxide emissions. Hotspots of deforestation during this period occurred in the central coast and highland regions of the country, especially within Nghệ An, Quảng Nam, Gia Lai, and Kon Tum. Focused protection of 20% of forests would reduce deforestation-related emissions by 86%.

Meanwhile, deforestation and draining of 9,700 hectares of peatland swamp per year between 2001 to 2023 led to about 17 million tons of CO_2-eq per year. Focused interventions on 20% of Vietnam's peatlands could reduce these emissions by 58%.

Improve Rice Production

Vietnam's rice fields emit 90 million tons of greenhouse gases a year and have the highest emissions per hectare at 14 tons CO_2-eq per hectare, which is twice the regional average. This is due to continuous flooding and triple cropping within the primary rice-growing areas – the Red River delta in the north and the Mekong River delta in the south.

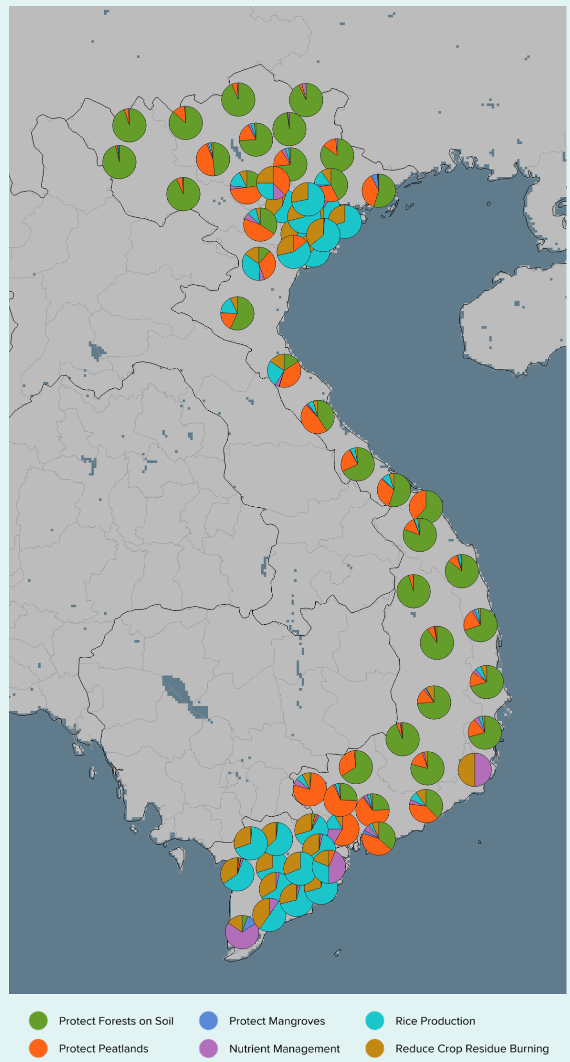


FIGURE 19. *Relative potential for climate solutions in the FALU sector in Vietnam, shown by the pie charts within each province.*

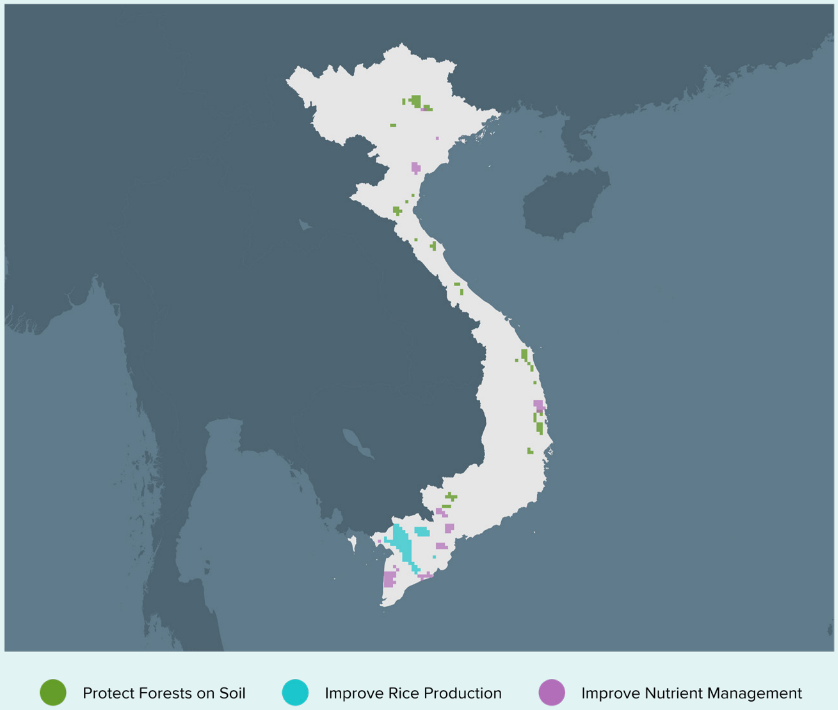


FIGURE 20. *Solutions hotspots in Vietnam, indicating locations where 20% of area provides an opportunity to address 86%, 63%, and 58% of possible emissions reductions for Protecting Forests on mineral soils, Improving Rice Production, and Improving Nutrient Management, respectively.*

Rice production within these deltas drives 10% of global rice methane emissions, yet Vietnam produces just 5% of global rice calories. Vietnam's rice fields, which are often double- or triple-cropped, are some of the highest-emitting farm fields in the world, even on a per-calorie-produced basis. Improving rice cultivation, primarily with non-continuous flooding, on 20% of Vietnam's fields would reduce emissions by 60%.

Rice straw burning is also practiced in these deltas. Burning crop residues generates methane and hazardous air pollution. In Vietnam, the practice produces 9.5 million tons CO_2-eq per year. Leaving residues on the field is one alternative to burning, and farmers can also use rice straw balers. When residues can be baled or otherwise collected from the field, they can be used for compost production, livestock feed and bedding, and various bioenergy applications (Dutta et al., 2022).

Reduce Food Waste and Improve Diets

After Indonesia, Vietnam has the highest potential to curtail emissions from food waste. The country wastes an average of 55 million tons of food a year, generating 110 million tons of CO_2 emissions. Halving food waste would reduce annual emissions by 55 million tons CO_2-eq. Improving diets in the country could reduce emissions by about 16 million tons CO_2-eq.

Indonesia

The largest and most populous country in the region, Indonesia has the highest national-level greenhouse gas emissions. Indonesia also has the largest area of peatlands and mangroves in Southeast Asia. Protecting forests on mineral soils and peatlands have the highest emissions reduction potential, followed by reducing FLW and strengthening mangrove protection.

FIGURE 21. *Solutions hotspots in Indonesia indicating locations where 20% of area provides an opportunity to address 79%, 63%, and 92% of possible emissions reductions for Protecting Forests on mineral soils, Improving Rice Production, and Improving Nutrient Management, respectively.*

Protect Forests, Mangroves, and Peatlands

Forests cover more than half of Indonesia's land area, and can be found on mineral soils, coastal mangroves, and peatlands. Preventing the loss of forests on mineral soils is the largest lever to reduce emissions since so much deforestation happens there. Deforestation on mineral soils, which occurred on 962,000 hectares between 2001 and 2023, resulted in about 646 million tons of CO_2 per year during this period. Protecting these forests could prevent those annual emissions, which would reduce national FALU emissions by 62%. However, without improved enforcement and incentives, protection of forests in Indonesia might only be as successful as it has been in recent years, during which time forest protection resulted in only a 16% decrease in clearing relative to unprotected forest areas.

Protecting peatlands is the second-largest lever for reducing greenhouse gas emissions in Indonesia. The country is home to more than 24 million hectares of tropical peatlands – about 80% of all of Southeast Asia's peatland area. Peatlands are diverse ecosystems characterized by waterlogged, carbon-rich peat soils consisting of partially decomposed plant material. These peatlands contain immense stores of soil carbon. The loss of carbon from trees and soils on peatlands was responsible for 378 million metric tons of carbon per year between 2001 and 2023.

In terms of per-hectare emissions savings, protecting peatlands is the largest lever to reduce emissions in Indonesia, reducing emissions by an average of 2,021 tons CO_2-eq per hectare.

Improve Rice Production

Java produces a majority of Indonesia's rice and is a hotspot of methane emissions from rice fields. These rice fields produce about 8.3 tons CO_2-eq per hectare, which is high for the region. Within the Barat, Tengah, and Timur provinces of Java, improved water management – using non-continuous flooding – can reduce annual emissions by about 4 million tons CO_2-eq without reducing rice yields. Within these provinces' 2.9 million hectares of rice fields, using non-continuous flooding could reduce emissions by 1.2 tons CO_2-eq per hectare, without reducing yields. Targeted interventions on 20% of Indonesia's rice-growing areas would generate 50% of the emissions savings.

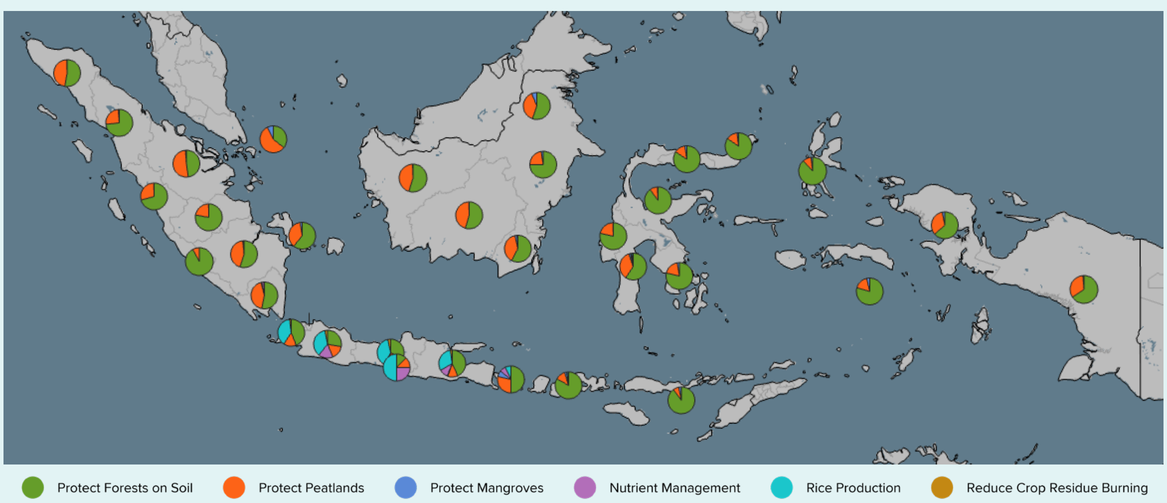


FIGURE 22. *Relative potential for climate solutions in the FALU sector in Indonesia, shown by the pie charts within each province.*

Reduce Food Waste and Improve Diets

Although the emissions savings from shifting diets and reducing food waste cannot be mapped directly, these emissions overlap with deforestation, land use change, and on-farm emissions within the region. However, emissions from imported foods are generated where they are grown.

Emissions from Indonesian diets are estimated at 870 million tons CO_2-eq on average. The consumption of ruminant meat (beef, goat, and lamb) in the country – totaling 3.4 kilograms per person per year – does not exceed the EAT-Lancet recommendations, which limits ruminant meat consumption to 98 grams per week, or 5.1 kilograms per year.

Indonesia wastes an average of 218 million tons of food per year, which is 22% of domestic food supply. Cutting food waste in half could save 104 million tons CO_2-eq emissions annually. Beef accounts for 131,000 tons of this waste, which is a small fraction (0.07%) of total food waste. However, eliminating the waste of beef could cut emissions by 12 million tons CO_2-eq, which represents 6% of food waste emissions.

Cambodia

Although about 40% of Cambodia's land area is protected, deforestation and land use change contribute more to national-level emissions than any other sector. Protecting forests on mineral soils, protecting peatlands, and reducing FLW have the highest emissions reduction potential.

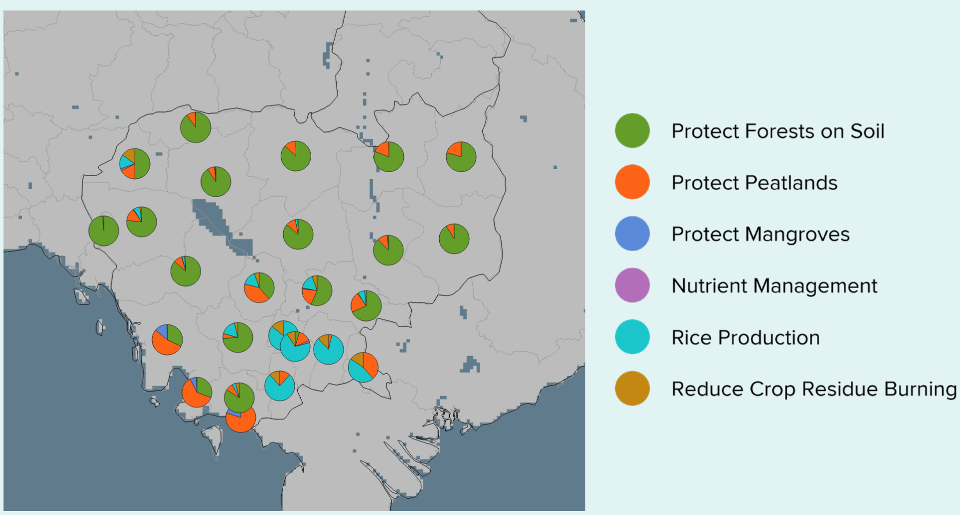


FIGURE 23. *Relative potential for climate solutions in the FALU sector in Cambodia, shown by the pie charts within each province.*

Protect Forests, Mangroves, and Peatlands

As in the region as a whole, reducing deforestation in Cambodia is the largest lever for reducing emissions within the FALU sector. In 2022, Cambodia had approximately 6.62 million hectares of natural forest on mineral soils remaining, extending over 36% of its land area.

According to the U.N. Environment Programme (UNEP), about 40% of these forests are protected, meaning development is prohibited or limited for ecological or cultural conservation. Countries with a high percentage of their forests under protection – such as Cambodia – often tend to be smaller countries or countries with fewer remaining forests.

However, between 2001 and 2023, 115,000 hectares of land were deforested per year, resulting in 68 million tons of CO_2-eq emissions. The production of commodities such as rubber, oil palm, and mined minerals has driven the bulk of the deforestation in Cambodia. Rubber production experienced a surge of expansion between 2001 and 2015, fueled by increasing international consumer demand. About 23 percent of all cleared forest in Cambodia was converted to rubber plantations during this time, and the establishment of plantations was closely correlated with global rubber prices.

Targeted protection of Cambodia's forests in 20% of forests in mineral soils could achieve a 75% reduction in deforestation-related emissions. Protecting Cambodia's 182,000 hectares of peatland could reduce emissions by 14 million tons CO2-eq.

BETWEEN 2001 AND 2023, 115,000 HECTARES OF LAND WERE DEFORESTED IN CAMBODIA PER YEAR, RESULTING IN 68 MILLION TONS OF CO_2-EQ EMISSIONS.

Philippines

Protecting carbon-rich forests and peatlands in the Philippines is a major lever to reduce emissions. Protecting these carbon-rich ecosystems could reduce emissions by 8 million and 6 million tons CO_2-eq, respectively. Solutions focused on improving rice production and nutrient management are highly concentrated in the country.

Improve Rice Production

Rice production is the biggest driver of emissions in the Philippines, responsible for 20 million tons of CO_2-eq emissions. The 4.5 million hectares of rice fields are located primarily in the north of the country. However, not all of the emissions from these fields are addressable without reducing yields. Focusing improvements to 20% of fields, especially in Bulacan province, would reduce emissions by 70%.

Improve Nutrient Management

Opportunities to reduce emissions from fertilizers are focused in the central and southern parts of the country. More targeted use of nitrogen fertilizers on the country's 8.5 million hectares could reduce emissions by 1.7 million tons CO_2-eq per year. Hotspots of excessive fertilizer use are pronounced within the Western Visayas and the SOCCSKARSGEN region, and the autonomous region in the south. Improving nutrient management on 20% of croplands in the Philippines could reduce emissions by 51%.

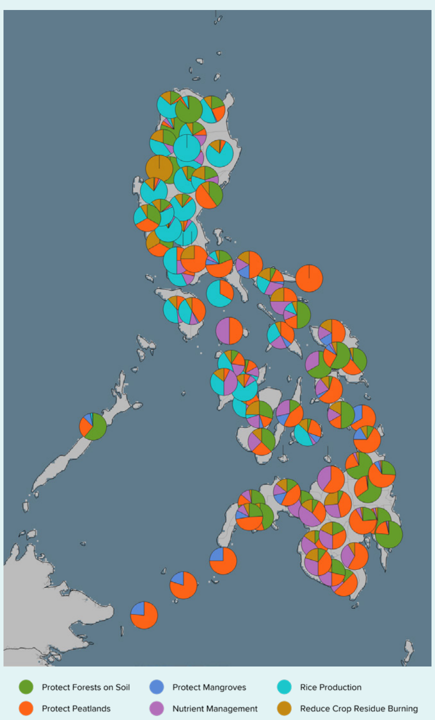


FIGURE 24. *Relative potential for climate solutions in the FALU sector in the Philippines, shown by the pie charts within each province.*

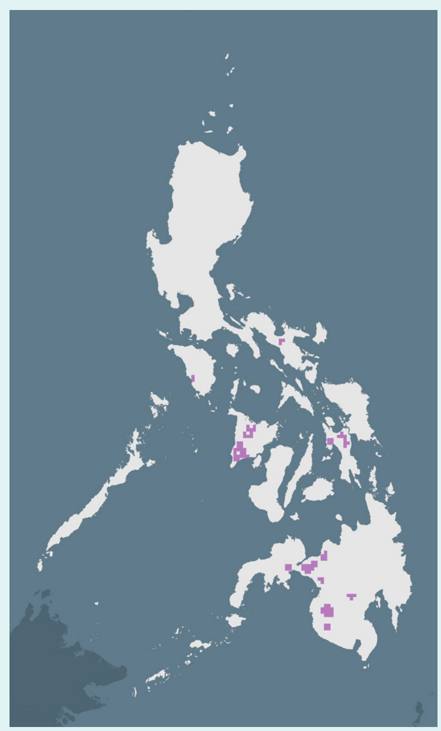


FIGURE 25. *Hotspots of nutrient management potential emissions savings in the Philippines.*

Thailand

Thailand has the greatest potential within Southeast Asia to reduce emissions from rice production. Deforestation on mineral soils is also a big lever within the country, and is focused in the northeast and the Malay peninsula. Land use change on peatlands also drives emissions on the Malay peninsula.

Improve Rice Production

Thailand is one of the region's top rice-producing countries. Throughout much of the country, improving rice production is the most important lever for reducing emissions (Figure 26). The crop is grown on 10.3 million hectares and results in about 60 million tons CO_2-eq emissions per year. Focusing non-continuous flooding and nutrient management on the 20% of rice-growing areas in the country that are hotspots could reduce about 40% of these emissions.

Protecting Forests, Mangroves, and Peatlands

As of 2020, about one third of Thailand's land cover was natural forest. Between 2001 and 2023, the country lost an average of 62,000 hectares of forest on mineral soils. This deforestation resulted in 35 million tons CO_2-eq emissions per year. Deforestation was prominent on the Malay peninsula, especially within the Surat Thani province. Focused protection of forests in Thailand could reduce emissions by 91%.

Thailand has about 63,000 hectares of peatlands, mainly in the south of the country and on the Malay peninsula. During the study period, peatland degradation generated 17 million tons CO_2-eq per year. Targeting protection to 20% of peatland area could reduce emissions from peatland degradation by 61%.

Diets and Food Waste

Thailand has low ruminant meat consumption, given its per capita GDP. The average diet in Thailand contains about 1.7 kilograms of ruminant meat per year, which is lower than the EAT-Lancet threshold of 5.1 kilograms a year, and lower than other countries with similar per capita GDP. Peru (5 kilograms), Gabon (5.8 kilograms), Georgia, (8.6 kilograms), and El Salvador (9.7 kilograms) all have similar per capita GDPs, but consume significantly more ruminant meat than Thailand. Halving food loss and waste could reduce emissions by 25 million tons CO_2-eq.

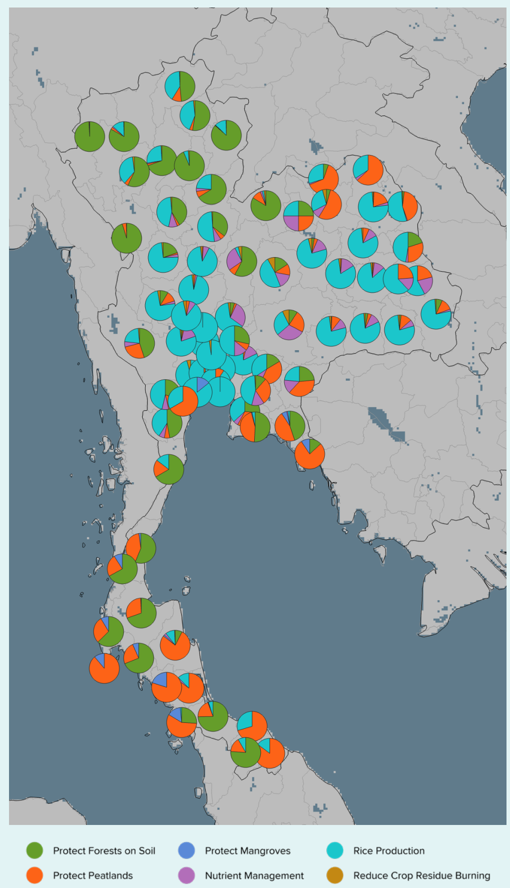


FIGURE 26. *Relative potential for climate solutions in the FALU sector in Thailand, shown by the pie charts within each province.*

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IMPLEMENTING CLIMATE SOLUTIONS: BENEFITS TO PEOPLE

OVERVIEW

Climate mitigation actions in the land use sector have many additional benefits, including improved air quality, heightened climate resilience, and more effective adaptation to extreme weather, according to the IPCC AR6 (Sixth Assessment Report) Working Group III Summary for Policymakers. Mitigation actions related to land use can also improve yields and increase farmer incomes, which contribute a disproportionate portion of Southeast Asia's regional GDP (Figure 3).

The health benefits of some mitigation actions – for example, implementing alternatives to burning rice straw, reducing fires on peatland, and clearing forest with fire – are particularly important in Southeast Asia, given the recurring air quality issues that these land clearing practices cause (Vadrevu, Ohara & Justice, 2018).

Another benefit of well-designed climate mitigation in the land use sector is protection of the region's natural ecosystems. Natural ecosystems can be protected directly by supporting the establishment of protected areas, or through forest-, peatland-, and mangrove restoration programs. Natural ecosystems can also be protected indirectly by reducing externalities associated with some agricultural practices. Improving nutrient management, for example, reduces levels of nitrous oxide – a powerful greenhouse gas – while also decreasing nitrate pollution and lowering the prevalence of marine "dead-zones" caused by hypoxia.[5]

This chapter explores the positive impacts of implementing climate solutions that generate mitigation benefits well beyond the reduction of greenhouse gas emissions. We analyze how such solutions provide various benefits to the environment, human well-being, and climate adaptation.

5 Hypoxia is a condition in which oxygen levels decrease due to competition with microorganisms that feed on excess fertilizer.

IMPROVE NUTRIENT MANAGEMENT

Food Security

Excessive nutrients – often a byproduct of fertilizer use – cause environmental problems in some parts of the world. Elsewhere, insufficient nutrients prove problematic because they result in lower agricultural yields (Foley et al., 2011). Targeted, site-specific, and efficient fertilizer use can improve crop productivity, improving food security globally (Mueller et al., 2012; Vanlauwe et al., 2015).

Health

Nitrate contamination of drinking water due to excessive runoff from agricultural fields has been linked to several health disorders, such as methemoglobinemia and cancer (Patel et al., 2022; Ward et al., 2018). Reducing nutrient runoff through better land management practices is critical to mitigate these risks (Ward et al., 2018).

Nitrogen oxides from fertilized croplands are important sources of agriculture-based air pollution. Improved management of nitrogen oxides, however, can decrease the prevalence of respiratory and cardiovascular disease (Almarez et al., 2018; Sobota et al., 2015).

Income and Work

Improved site-specific nutrient management reduces farmers' input costs and increases profitability (Cassman et al., 2021; Rurinda et al., 2020). A review of 61 studies across 11 countries – including Thailand, Vietnam, Indonesia, Malaysia, and the Philippines – revealed that site-specific nutrient management resulted in an average yield increase of 12%, and increased farmers' income by 15% while simultaneously improving nitrogen use efficiency (Chivenge et al., 2021).

Water Quality

Nutrient runoff from agricultural systems is a major driver of water pollution globally, leading to eutrophication and hypoxic zones in aquatic ecosystems (Bijay-Singh & Craswell, 2021).[6] Nitrogen pollution also harms terrestrial biodiversity through soil acidification, and increases the productivity of fast-growing species, including invasives, which can outcompete native species (Porter et al., 2013). Improved nutrient management is necessary to reduce nitrogen and phosphorus loads not only in water bodies (Withers et al., 2014; van Grinsven et al., 2019), but also in terrestrial ecosystems (Porter et al., 2013). Such practices have proven effective in reducing harmful algal blooms and preserving biodiversity in sensitive water ecosystems (Scavia et al., 2014).

Resilience to Drought

Balanced nutrient concentration contributes to long-term soil fertility and improved soil health by enhancing organic matter content, increasing microbial diversity, and facilitating nutrient cycling (Antil & Raj, 2019; Selim, 2020). Healthy soil also experiences reduced erosion and has higher water content, which in turn increases its resilience to droughts and extreme heat (Rockström et al., 2017).

6 Eutrophication occurs when aquatic environments are enriched with nutrients such as nitrogen or phosphorus that leads to algal blooms. This leads to low-oxygen waters that can kill fish and seagrass and reduce essential fish habitats.

IMPROVE RICE PRODUCTION

The additional benefits of improved rice production arise from all the practices – including alternate wetting and drying (AWD), and improved nutrient management – that comprise this solution.

Water Quality

Both non-continuous flooding, also known as AWD, and improved nutrient management mitigate water pollution. By minimizing continuous submersion, AWD reduces nutrient and pesticide runoff into water bodies. In contrast, improved nutrient management reduces the excess fertilizers that could potentially be deposited in local water bodies. Both mechanisms mitigate eutrophication and harmful algal blooms, protect aquatic ecosystems, and ensure safer drinking water supplies (Bouman et al., 2007; Richards & Sander, 2014).

Water Conservation

Field studies across South and Southeast Asia have shown that AWD can typically reduce irrigation requirements by 20–30% compared to conventional flooded systems without adversely affecting rice yield or grain quality (Suwanmaneepong et al., 2023; Carrijo et al., 2017; Tuong et al., 2005). This reduction in water usage alleviates pressure on water resources, especially in drought-prone areas (Alauddin et al., 2020).

Health

AWD can reduce the accumulation of arsenic, a carcinogen that is responsible for thousands of premature deaths in South and Southeast Asia, in rice grains (Jameel et al., 2021; Ishfaq et al., 2020). The amount of arsenic mitigated can vary from 0–90%, depending upon the timing of the AWD (Ishfaq et al., 2020).

Soil Health

Improved nutrient management of rice production can enhance soil fertility and health, increasing its resilience to extreme heat and droughts. AWD also slows down the rate of soil salinization, thereby protecting soil from degradation (Carrijo et al., 2017).

PREVENTING DEFORESTATION

Food Security

Protecting forests in predominantly natural areas bolsters food security by enhancing food availability, dietary diversity, and income opportunities. A global review of 65 studies found that more than 75% reported positive impacts on food and nutrition security, either via the direct provision of forest foods or via the indirect effects of forest-based ecosystem services on surrounding agricultural lands (Olesen et al., 2022). One study found that protecting 58% of threatened forests in Southeast Asia could support the dietary needs of approximately 305,000–342,000 people annually (Sarira et al., 2022). Forests also provide a key source of income, supporting the livelihoods for subsistence households and individuals (de Souza et al., 2016; Herrera et al., 2017; Naidoo et al., 2019). By maintaining this source of income through forest protection, households can earn sufficient income to ensure food security.

Health

Protected forests can benefit the health and well-being of surrounding communities via positive impacts on the environment and local economies. Biodiversity-rich protected areas promote more income-earning opportunities and improve health outcomes, with children near protected forests showing higher dietary diversity and better overall health than those in deforested areas (Naidoo et al., 2019). In contrast, deforestation is linked to higher incidences of diseases like malaria in tropical regions (Fornace et al., 2016; Burkett-Cadena & Victor, 2018; Karuppusamy et al., 2021), subpar air quality (Butt et al., 2021), and poor child health (Cordoba, 2024; Pienkowski et al., 2018). Reducing deforestation improves public health by lowering vector-borne diseases, mitigating extreme weather impacts, and improving air quality (Reddington et al., 2015).

Water Security and Quality

Forests serve as a natural filter that helps maintain healthy water quality in local water bodies, since forests prevent soil erosion and absorb nutrients (Filoso et al., 2017; Sweeney et al., 2004). Deforestation, by comparison, typically increases surface runoff since less water is intercepted (Robinson et al., 2022). Field studies from the tropics have shown that logging primary forests and subsequent establishment of agricultural or pastoral lands or urbanization generally results in downstream nutrient enrichment (Tanaka et al., 2021).

Forests are also essential for regulating moisture that contributes to precipitation in continental interiors (Filoso et al., 2017). Widespread deforestation, agricultural expansion, and urban growth may even adversely affect global rainfall patterns (Ellison et al., 2011). A recent pantropical study analyzing satellite data from 2003-2017 revealed that forest loss caused significant reductions in precipitation over spatial scales from 50 to 200 kilometers (Smith et al., 2023). The study also projected that deforestation in Southeast Asia could decrease local precipitation by 5 millimeters by 2100.

Resilience to Extreme Weather Events

Protected forests are more biodiverse and therefore more resilient and adaptable, providing higher-quality ecosystem services to surrounding communities (Gray et al., 2016). Forests and trees provide income diversification and serve as an adaptive strategy for rural communities in low-and middle-income countries. Examples from Tanzania, Peru, India, and Bangladesh have shown that timber and non-timber forest products present essential income diversification strategies for rural communities facing increased climate variability and climate hazard risks (Pramova et al., 2012). By increasing the diversity of plant species, forest preservation can strengthen tolerance of drought and fire as well (Buotte et al., 2020). Forests also help regulate local climate by reducing temperature extremes, and studies have shown that the extent of forest coverage helps alleviate vulnerability associated with heat effects (Lawrence et al., 2022; Walton et al., 2016). Meanwhile, tropical deforestation threatens human well-being because it reduces the critical local cooling effects that tropical forests provide, exacerbating extreme heat conditions in these regions, which are already highly vulnerable to the impacts of climate change (Seymour, Wolosin & Gray, 2022).

Equality

Indigenous peoples have a long history of caring for and shaping landscapes that are rich with biodiversity (Fletcher et al., 2021). Indigenous communities provide vital ecological functions for preserving biodiversity, including seed dispersal and predation (Bliege Bird & Nimmo, 2018). Indigenous peoples also have spiritual and cultural ties to their lands (Garnett et al., 2018). Establishing protected areas must prioritize the return of landscapes to Indigenous peoples so that traditional owners can experience the benefits of biodiversity. However, the burden of conservation should not be placed on Indigenous communities without legal recognition or support (Fa et al., 2020). In fact, land grabs and encroachments on Indigenous lands have increased the likelihood of deforestation (Sze et al., 2022). Efforts to protect forests must include legal recognition of Indigenous ownership in order to support a just and sustainable conservation process (Fletcher et al., 2021).

PROTECTING MANGROVES

Food Security

Mangroves support the development of numerous commercially important species and strengthen the overall productivity of fisheries. Mangroves enhance fisheries by contributing primary productivity that underpins marine food chains and offering suitable habitats for many fishery species (Hutchison et al., 2014). Mangroves also serve as critical nursery grounds during the juvenile development stages of certain species, supporting the development of numerous commercially important species and strengthening overall fishery productivity. For example, research conducted across 6,000 villages in Indonesia found that rural coastal households near high- and medium-density mangroves consumed higher amounts of fish and aquatic animals in comparison to households without mangroves nearby (Ickowitz et al., 2023). This underscores the critical role of mangroves in supporting food security and nutrition for Indonesia's coastal communities. Similarly, the Sundarbans mangrove forest in Bangladesh and India provides food sources such as fish, honey, and crabs that support millions of people living in the region (Uddin et al., 2013).

Income and Work

Mangroves are a significant contributor to local livelihoods, providing employment for a significant coastal population across the globe via the fisheries and tourism that they support. Coastal ecosystems such as mangroves are crucial for subsistence fisheries, and they sustain approximately 4.1 million small-scale fishers (Leal & Spalding, 2022). In Bangladesh and India, the majority of residents living in the Sundarbans depend directly or indirectly on mangrove systems (Uddin et al., 2013; Sarkar et al., 2024). In Indonesia, mangrove restoration has increased fish yields while reducing costs and increasing profits (World Bank, 2023).

Resilience to Extreme Weather Events

Mangroves mitigate the psychological and physical toll of extreme events, including storm surges, tsunamis, and sea-level rise. Specifically, mangroves reduce erosion through their aerial root structure, which retains sediments that would otherwise degrade the shoreline (Thampanya et al., 2006). For vulnerable communities, the protective functions of ecosystems like mangroves are vital. Mangroves protect more than 60 million people in low-lying coastal areas, mainly in developing countries (Hochard et al., 2021). Mangroves also provide an estimated US$65 billion in flood protection globally (Menéndez et al., 2020). For example, it is estimated that during the 1999 cyclone that struck Orissa, India, mangrove forests were critical in preventing loss of lives and lowering economic damages (Das & Crepin, 2013). Similarly, during the 2004 mega tsunami, it is estimated that mangroves and coastal vegetation reduced the loss of lives by 5% in Aceh, Indonesia (Bayas et al., 2011).

PROTECTING PEATLAND

Climate Adaptation

Peatland protection can help communities adapt to extreme weather. Because peatlands regulate water flows, they can reduce the risk of droughts and floods (IUCN, 2021; Ritson et al., 2016). Evidence suggests that peatlands can provide a cooling effect in their immediate environment, lowering daytime temperatures and reducing temperature extremes between day and night (Dietrich & Behrendt, 2022; Helbig et al., 2020; Worrall et al., 2022).

Health

When peatlands are drained, they are susceptible to fire. Peatland fires can significantly contribute to air pollution because of the way these fires smolder (Uda et al., 2019). Smoke and pollutants – particularly PM2.5 – from peatland fires can harm respiratory health and lead to premature mortality (Marlier et al., 2019).[7] A study of peatland fires in Indonesia estimated they contribute to the premature mortality of about 33,100 adults and 2,900 infants annually (Hein et al., 2022). Researchers have linked exposure to PM2.5 from peatland fires to increased hospitalizations, asthma rates, and lost workdays (Hein et al., 2022). Peatland protection mitigates exposure to air pollution and can save money due to reduced health-care expenditures (Kiely et al., 2021).

Income and Work

Peatlands support the livelihoods of nearby communities, especially those in low- and middle-income countries (Schulz et al., 2019; Thornton et al., 2020). Peatlands can also support the livelihoods of women, contributing to gender equality. For example, raw materials – purun – from Indonesian peatlands are used by women to create and sell mats used in significant events such as births, weddings, and burials (Goib et al., 2018).

Nature Protection

Peatlands are home to a wide range of species, supporting biodiversity of flora and an abundance of wildlife (UNEP, 2022; Minayeva et al., 2017; Posa et al., 2011). Because of their unique ecosystem, peatlands provide a habitat for many rare and threatened species (Posa et al., 2011).[8] A study of Indonesian peat swamps found that the IUCN Red List classified approximately 45% of mammals and 33% of birds living in these ecosystems as threatened, vulnerable, or endangered (Posa et al., 2011). Indonesia's peatlands provide habitats for several threatened species like orangutans, gibbons, and Sumatran tigers (Harrison and Rieley, 2018). Peatlands in Papua and West Papua are freshwater biodiversity hotspots, while those in Central Kalimantan host more than 1,100 species, including 46 globally threatened species (Husson et al., 2018; Harrison & Rieley, 2018). Peatlands also support a variety of insect species (Spitzer & Danks, 2006). Because of their sensitivity to environmental changes, some peatland insects can serve as indicators of peatland health and play a role in conservation efforts (Spitzer & Danks, 2006). Protecting these peatlands and restoring degraded peatland ecosystems are vital to reducing extinction risk in these biodiversity hotspots (Tan et al., 2022).

Water Resources

Peatlands filter water pollutants and improve water quality and are important sources of potable water for some populations (Minayeva et al., 2017). One study estimated that peatlands store about 10% of freshwater globally, not including glacial water (Xu et al., 2018a). Peatlands play a significant role in local water management by naturally regulating water flow (Terzano et al., 2023). Protecting and restoring peatlands allows these ecosystems to serve as a natural flood management mechanism. For example, during heavy precipitation events, peatlands can store rainfall, thereby reducing flood risks, and during dry periods, peatlands can release stored water and reduce the impact of droughts (Allot et al., 2019; Gatis et al., 2023; Karimi et al., 2024). Additionally, peatlands contribute to improving downstream water quality by filtering pollutants (UNEP, 2019).

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7 PM2.5 refers to particulate matter of size less than 2.5 micrometers in diameter; breathing in these particles can lead to adverse health consequences.
8 IUCN Red List is a list of the most threatened species, maintained by the International Union for Conservation of Nature.

REDUCING FOOD LOSS AND WASTE

Food Security

Reducing food loss and waste (FLW) increases the amount of available food, thereby improving food security without requiring increased production (Neff et al., 2015). The World Resources Institute estimated that halving the rate of FLW could reduce the projected global need for food by approximately 20% by 2050 (Searchinger et al., 2019). These studies demonstrate that reducing FLW can simultaneously decrease the demand for food production while improving food security.

Health

Policies that reduce food waste at the consumer level – such as improved food packaging and clearer information on shelf life and date labels – can reduce the number of foodborne illnesses (Neff et al., 2015). Additionally, efforts to improve food storage and food handling can further reduce illnesses and improve working conditions for food supply-chain workers (Neff et al., 2015). Reducing FLW can also lower air pollution from production, processing, and transportation, and from the disposal of wasted food (Nutrition Connect, 2023). One study found that reducing FLW can improve air quality – primarily through reductions in CO, NH_3, nitrogen oxides, and $PM_{2.5}$ – which lowers premature mortality from respiratory infections (Gatto & Chepeliev, 2024). These benefits were primarily observed in China, India, and Indonesia, where high FLW-embedded air pollution is prevalent across all stages of the food supply chain (Gatto & Chepeliev, 2024).

Climate Adaptation

Households and communities can strengthen adaptation to climate change by improving food storage, which helps reduce food loss (Ziervogel & Ericksen, 2010). Better food storage infrastructure also improves food security from extreme weather events such as droughts or floods, which make it more difficult to grow food and can disrupt food distribution (Mbow et. al, 2020).

Income and Work

FLW accounts for a loss of about US$1 trillion annually (World Bank, 2020). Household-level savings are particularly important for low-income families, as these households commonly spend a higher proportion of their income on food (Davidenko & Sweitzer, 2024). Reducing FLW can also improve economic efficiency (Jaglo et al., 2021). In fact, one report found efforts to reduce food waste produced positive returns on investments in cities, businesses, and households in the United Kingdom (Hanson & Mitchell, 2017).

Land and Water Resources

Reducing FLW can conserve land and water resources and improve biodiversity (Cattaneo, Federighi, & Vaz, 2021). A reduction in FLW reflects improvements in resource efficiency of freshwater, synthetic fertilizers, and cropland used for agriculture (Kummu et al., 2012). Reducing the strain on freshwater resources is particularly relevant in water-scarce areas; one assessment found that FLW squandered around 46 trillion gallons of water annually, which represents one-quarter of the total water used for agriculture (Kummu et al., 2012).

CHANGING DIETS

Health

Reducing ruminant meat consumption has multiple health benefits. Diets high in red meat have been linked to increased risk of mortality, and mortality from cancer specifically (Pan et al, 2012; Sinha et al., 2009). Excess red meat consumption is also associated with increased risk of cardiovascular disease, stroke, type 2 diabetes, colorectal cancer, and weight gain (Bouvard et al., 2015; Bradbury et al., 2020; Kaluza et al., 2012; Pan et al., 2011; Verngaud et al., 2010). Meanwhile, diets that incorporate other sources of protein like fish, poultry, nuts, legumes, low-fat dairy, and whole grains are associated with a lower risk of mortality as well as a reduction in dietary saturated fat, and can improve the management of diabetes (Pan et al., 2012; Nelson et al., 2016; Toumpanakis et al., 2018).

A reduction in the demand for meat can have implications for health outcomes associated with livestock production. Animal agriculture – especially industrial and confined feeding operations – commonly uses antibiotics to prevent and treat infections in livestock (Casey et al., 2013). Consistent direct contact with livestock exposes people, especially farmworkers, to antibiotic-resistant bacteria, which can lead to antibiotic-resistant health outcomes (Sun et al., 2020; Tang et al., 2017).

Water Resources

While livestock directly uses a small proportion of water withdrawals, a significant amount of water is required to produce forage and grain for animals (Steinfeld et al., 2006). Ruminant meats have some of the highest water footprints of animal protein sources (Steinfeld et al., 2006; Kim et al., 2020; Searchinger et al., 2019).

Water Quality

Livestock production can contribute to water pollution directly and indirectly through feed production and processing (Steinfeld et al., 2006). Manure, for example, contains nutrients like nitrogen and phosphorus, drug residues, heavy metals, and pathogens (Steinfeld et al., 2006). Manure can pollute water directly from farms and can also leach into water sources when it is used as a fertilizer on croplands (Porter & Cox, 2020).

Land Use

Animal agriculture – especially ruminants like cattle – requires a lot of land to raise (Nijdam et al., 2012). Life cycle analyses have found that beef consistently requires the most land use among animal-based proteins (Nijdam et al., 2012; Meier & Christen, 2013; Searchinger et al., 2019). This high land use reflects the amount of land needed to grow crops that eventually feed livestock (Ripple et al., 2014a). Reducing the consumption of meat, dairy, and eggs can result in per capita reductions in cropland use (Westhoek et al., 2014).

Biodiversity

Agricultural expansion for livestock production is a major driver of deforestation (Ripple et al., 2014b). Deforestation is associated with a loss of biodiversity through habitat degradation and destruction, and through forest fragmentation (Steinfeld et al., 2006). Livestock farming can reduce the diversity of landscapes and can contribute to the species loss of large carnivores, herbivores, and birds (Ripple et al., 2015; Steinfeld et al., 2006). The clearing of forests for animal agriculture is especially prevalent in the tropics, and a lower demand for meat – particularly ruminant meat – could reduce tropical deforestation (Ripple et al., 2014b).

Air Quality

In addition to CO_2, ruminant agriculture is a source of air pollutants like methane, nitrous oxides, ammonia, and volatile organic compounds (Gerber et al., 2013). The fertilization of feed crops and the deposition of manure on crops are the primary sources of nitrogen emissions from ruminant agriculture (Steinfeld et al., 2006). Air pollution in nearby communities can also produce poor odors, which may affect residents' stress levels and quality of life (Heederik et al., 2007).

Food Security

Reducing ruminant meat in the diets of residents of high-income countries can improve food security and can lead to more equitable diets in low-income countries (Searchinger et al., 2019). Productive cropland that is currently used to grow animal feed could instead be used to produce food for human consumption (Ripple et al., 2014a).

Equality

A lower demand for ruminant meat could promote environmental justice by reducing the number of industrial animal agriculture operations. This may benefit communities near these operations by reducing exposure to air and water pollution, pathogens, and odors (Steinfeld et al., 2006; Casey et al., 2013; Heederik et al., 2007).

BURNING RICE STRAW

Air Pollution

Rice straw burning following the end of the growing season is a major source of air pollution – including fine particulate matter, CO_2 and CO – in South and Southeast Asia, particularly in India, Pakistan, Nepal, and Bangladesh (Jain et al., 2014; Kaskaoutis et al., 2014; Na Talang et al., 2024; Lan et al., 2022; Sharma et al., 2010; Singh et al., 2021). In Vietnam's Red River delta, for example, rice burning contributed 29.5 Gg of PM10, 27 Gg of PM2.5, and 1.6 Gg of black carbon in 2018 (Le et al., 2020).[9] In Thailand, levels of PM10 during the rice-burning months are twice as high as during non-burning months (Junpen et al., 2018). Avoiding rice burning can reduce harmful air pollutants such as particulate matter and black carbon in densely populated rice-growing regions (Venkataraman et al., 2018). Alternatives to burning, such as composting, biogas generation, ruminant feed, or producing composite materials, can significantly reduce the air pollution associated with rice burning (Singh et al., 2021).

Health

Since fine particulate matter and black carbon make up a large portion of pollution from rice straw burning, the practice can contribute to poor air quality in areas located far from agricultural fields (Kaskaoutis et al., 2014). Poor air quality from burning is particularly harmful to human health and can lead to premature mortality in Southeast Asia (Lan et al. 2022). Air pollution from burning rice straw and other crop residue burning has been linked to eye irritation, headaches, nausea, skin irritation, allergies, respiratory infections, increased risk of lung cancer, and reduced lung function (Raza et al., 2022; Huang et al., 2022; Gupta, 2019). Farmers have reported increasing severity of chronic illnesses during burning, and poorer productivity at work due to illness (Raza et al., 2022). Exposure to air pollution is particularly harmful for children and their future health as they age; one study found that children living near agricultural fields had poorer lung function during periods of crop burning (Gupta et al., 2019). Sustainable residue management practices can help reduce morbidity and mortality and can significantly reduce health costs associated with crop residue burning (Raza et al., 2022).

Land Resources

Rice and other crop residue burning can significantly degrade soils since burning leads to a loss of nutrients – especially nitrogen – that would otherwise be retained in the soil (Bhuvaneshwari et al., 2019). In areas of northern India where rice straw burning is common, for example, soils have very low nitrogen content compared to other regions of the country where crop burning is less common (Kumar et al., 2015). Burning also raises soil temperatures, which can kill beneficial microorganisms (Bhuvaneshwari et al., 2019). Studies have found that retaining crop residue on agricultural fields can benefit soil quality, soil organic carbon, soil moisture, nutrient cycling, and soil retention (Fu et al., 2021; Turmel et al., 2015). Meanwhile, at experimental field sites in India and Bhutan where rice straw and other crop residue were used as mulch rather than burned, agricultural production increased between 36-64% (Dey et al., 2020).

9 PM10 refers to particulate matter less than 10 micrometers in diameter; breathing in these particles can lead to adverse health consequences.

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TOPICAL CHAPTERS

PROTECT FORESTS, INCLUDING MANGROVES

Overview

In this chapter, we delve into estimated deforestation in Southeast Asia and explain how we calculated hotspots. We then summarize emissions from vegetation and soils associated with deforestation and discuss our methods for this analysis. In this chapter, we present differentiated results for deforestation on mineral soils, peatlands, and mangroves.

Forests store carbon in biomass and soils and serve as carbon sinks, taking up an estimated 12.8 Gt CO_2-eq a year globally, including mangroves and forested peatlands (Pan et al., 2024). Carbon stored in forests is released into the atmosphere through deforestation and degradation, which refer to forest clearing or reductions in ecosystem integrity from human influence (DellaSala et al., 2025).

Scope of Deforestation

Forests dominate the Southeast Asian landscape. The region is home to nearly 15% of the world's tropical forests, but has some of the world's highest rates of deforestation . In this analysis, we calculated deforestation using Hansen et al. data (Figure 27), developed for Global Forest Watch and included tree cover and tree cover loss data from January 2001 to December 2023. This data served as the best estimate as of November 2024.

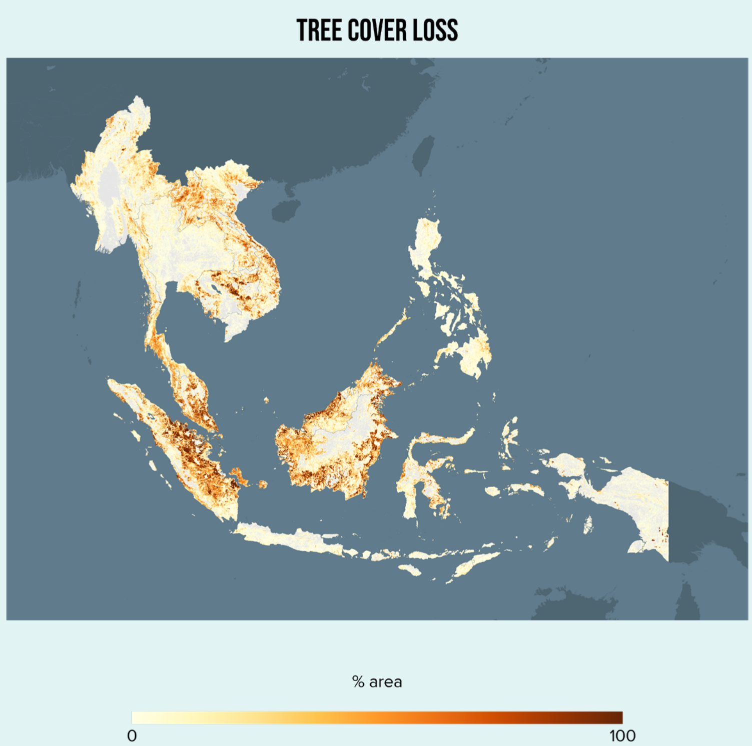

FIGURE 27. *Forest lost during the study period (2001-2023). Data source: Hansen et al. (2013).*

Deforestation emissions are particularly large in Southeast Asia. This is because forest ecosystems are dominant in the region and because natural ecosystems in Southeast Asia are unusually high in carbon. In this chapter, we discuss how protection of forest ecosystems impacts mineral soils and mangrove forests.

The carbon density of Southeast Asian forests is exceptionally high. There are several carbon pools that contribute to these high levels of carbon: above- and below-ground woody mass, and carbon in mineral and organic soils. Carbon in soils is so high in Southeast Asia because of the extent of both peatlands and mangroves, each of which contains more carbon per square meter of land than any other ecosystem.

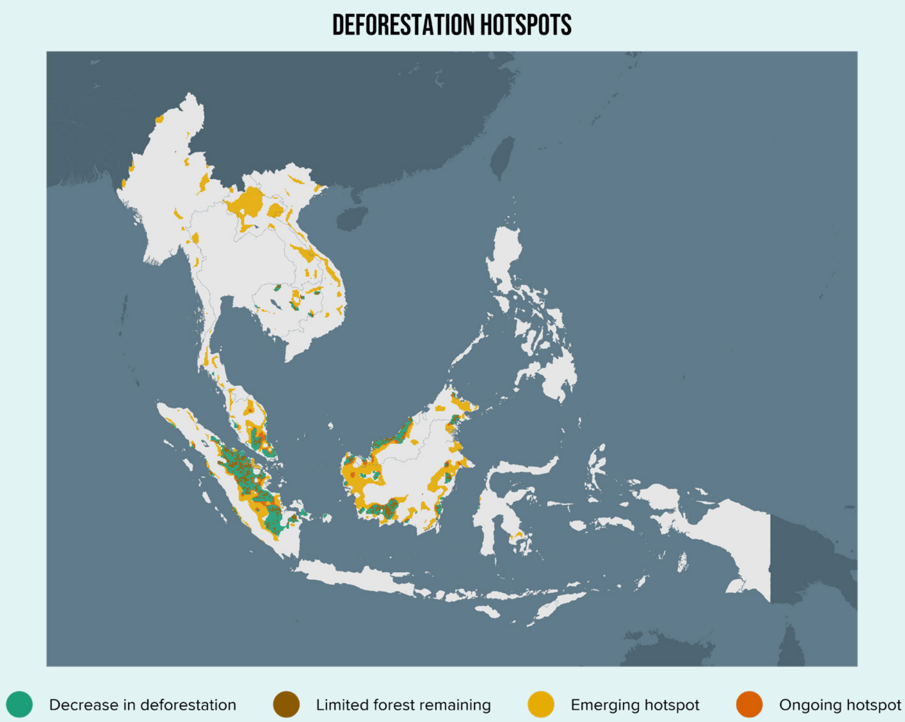

FIGURE 28. *Hotspots of forest loss from 2012 to 2023.*

Between 2001 and 2023, Southeast Asia lost about 1.8 million hectares (ha) of forest per year (an annual rate of 0.7%). This deforestation resulted in 1.2 billion tons of CO_2-eq. emissions per year. This is the largest source of emissions in Southeast Asia, meaning protection of these forests is the largest lever to reduce emissions.

Tropical rain forests on mineral soils are big stores of carbon, containing about 650 metric tons of carbon dioxide equivalent per hectare (or the equivalent emissions of 10 cars over their lifetimes). We distinguish forests on mineral soils (formed from the weathering of rocks) from those on wetter organic soils (found in peatlands) because the soils of peatland and mangrove areas contain more organic matter and carbon than mineral soils.

Assessing hotspots of deforestation

Hotspots of deforestation are defined as regions with deforestation rates such that 25% of forested area undergoes tree cover loss within a decade (See Methods Appendix for detailed methods). We define forests using the definition of "tree cover" in Hansen et al. We define year by year forest cover as year 2000 forest cover minus yearly forest cover loss.

We identify a subset of hotspots of deforestation, indicated in Figure 28, which represent the areas where deforestation was an ongoing threat from 2012 to 2023. In many parts of Indonesia, especially on Sumatra and Kalimantan, rates of deforestation are declining relative to the period from 2001 to 2012 (Figure 28). Emissions from deforestation have also declined (Figure 29).

Forest Protection

One of the direct solutions for addressing deforestation and land use change is legal protection. We consider forests to be protected if they are 1) formally designated as protected areas (UNEP-WCMC & IUCN, 2024), or are 2) mapped as Indigenous peoples' lands in the global study by Garnett et al. (2018).

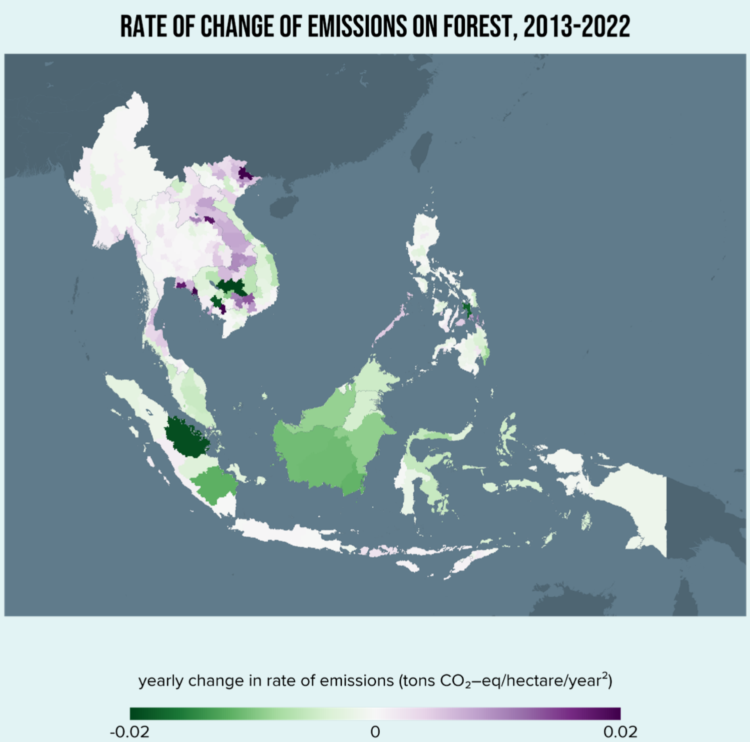

FIGURE 29. *Classification of provinces into regions of decreased deforestation (green) versus increased deforestation (purple). Negative values indicate that emissions are decreasing from year to year.*

Most of the forests in the Southeast Asia region are home to tens of millions of Indigenous peoples whose existence is guaranteed under countries' constitutions and international covenants (Colchester, 2011). Indigenous peoples' lands and protected areas reduce – but do not eliminate – forest clearing relative to unprotected areas (Baragwanath et al., 2020; Blackman & Viet, 2018; Li et al., 2024; McNicol et al., 2023; Sze et al., 2022; Wolf et al., 2023; Wade et al., 2020).

In this analysis, we assume protected forests maintain all their carbon when we estimate the emissions benefits of protected forests. However, we have also quantified the emissions savings of forest protection based on estimates of current protected area–effectiveness (Table 2). Improving management to further reduce land use change within protected areas is a critical component of forest protection (Jones et al., 2018; Meng et al., 2023; Vijay et al., 2018; Visconti et al., 2019; Watson et al., 2014).

Globally, Wolf et al. (2021) found that rates of forest loss inside protected areas are 40.5% lower on average than in unprotected areas, while Li et al. (2024) estimated that overall forest loss is 14% lower in protected areas relative to unprotected areas. Regional studies find similar average effects of protected areas on deforestation rates. For instance, Graham et al. (2021) reported 69% lower deforestation rates in protected areas relative to unprotected areas in Southeast Asia. During the 21st century to date, forest protection measures in Southeast Asia have been, on average, about 29% effective at conserving forests, based on the forest-area-weighted average of the reported effectiveness.

The International Union for Conservation of Nature (IUCN) defines protected areas as areas managed primarily for the long-term conservation of nature and ecosystem services. Much of the extent of Indigenous peoples' lands has not been fully mapped nor recognized for its conservation benefits (Garnett et al., 2018). Innovative and equity-driven strategies for forest protection that recognize the land rights, sovereignty, and stewardship of Indigenous peoples and local communities are critical for achieving just and effective forest protection globally (Dawson et al., 2024; Fa et al., 2020; FAO, 2024; Garnett et al., 2018; Tran et al., 2020; Zafra-Calvo et al., 2017).

Market-based strategies and other policies can complement legal protections by increasing the value of intact forests and reducing incentives for clearing (Garett et al., 2019; Golub et al., 2021; Heilmayr et al., 2020; Lambin et al., 2018; Levy et al., 2023; Macdonald et al., 2024; Marin et al., 2022; Villoria et al., 2022; West et al., 2023). The estimates in this report are based on legal protection alone because the effectiveness of market-based strategies is difficult to quantify, but strategies such as sustainable commodities programs, reducing or redirecting agricultural subsidies, and strategic infrastructure can also aid in protection.

TABLE 2. *Country level protection effectiveness*

Country	Protection Effectiveness
Brunei	42%
Cambodia	18%
Indonesia	17%
Laos	57%
Malaysia	55%
Myanmar	35%
Philippines	31%
Singapore	42%
Thailand	72%
Timor Leste	42%
Vietnam	44%

A 2021 IUCN study found that protected areas that had completed management reporting using the Management Effectiveness Tracking Tool (METT) conserved significantly more forest cover and forest carbon stocks than those that had not. The METT, or Tracking Tool, was developed to help track and monitor progress in the achievement of the World Bank/ WWF Alliance worldwide protected area management effectiveness target. It is also hoped that the Tracking Tool will be used more generally where it can help monitor progress towards improving management effectiveness.

Empirical effectiveness of forest protection

In the real world, protected forests are sometimes subject to land use change.

We base an estimate on the real-world effectiveness of forest protection on results of Wolf et al., which calculates the difference in deforestation rates between lands that are protected and those that are unprotected. We perform a weighted average over the reported rates in Vietnam, Indonesia, the Philippines, Thailand, Cambodia, Laos, Myanmar, and Malaysia, and find that average effectiveness of forest protection is 29%. In other words, protecting forest makes forest cover loss 29% less likely than leaving that forest unprotected. Country-specific protection effectiveness percentages from Wolf et al. are shown in Table 2.

Total annual emissions of forest loss between 2001 and 2023 were 1.2 billion tons CO_2-eq. In theory, protecting these forests could save 1.2 billion tons CO_2-eq annually. However, based on the weighted average of protection effectiveness, approximately 29% emissions savings may realistically be only 331 million tons CO_2-eq per year.

Method Details

Assessing deforestation emissions

We assess deforestation emissions using a “committed flux” method which assigns future carbon emissions when the dominant land use change event takes place. A contrasting method is the “bookkeeping” method which assesses emissions in the year that the emissions take place.

While the bookkeeping method is considered more scientifically accurate – it estimates emissions fluxes when they take place, which can be years after a land use change event – the committed flux method paints a picture that is more relevant to actors trying to address deforestation. For example, if interventions in Malaysia lead to a decrease in tree cover loss, a committed flux approach will show this more quickly than a bookkeeping method.

In the context of Southeast Asia, the estimates we find for emissions using the committed flux method are similar to emissions calculated using the bookkeeping method. The most widely cited source for bookkeeping method emissions are the greenhouse gas emissions fluxes calculated by Harris et al., which was updated to 2022-2023 difference year and downloaded from the World Resources Institute (Harris et al., 2021). While we only used these fluxes for comparison to our committed flux methods, we did use the associated deforestation data to assess deforestation rates and locations (Hansen et al., 2013; Gibbs et al., 2024).

The emissions associated with deforestation are assessed with the assumption that all carbon in woody biomass and some fraction of carbon in the soil will be emitted at some point. In the case of deforestation on mineral soils, we assume that all carbon will eventually be emitted in the form of CO_2. In the case of deforestation of mangrove ecosystems, we assume subsequent land use will be for aquaculture, and thus use an estimate for at-risk carbon consistent with the high-end estimate from Donato et al. (2011), in which all woody biomass, and 50% of the soil carbon, will eventually be emitted. For peatland ecosystem deforestation, we assume that all woody biomass carbon, and 30 years of flux from oxidizing peatlands, will eventually be emitted as CO_2. These methods have been developed in conjunction with the Project Drawdown Explorer and are explained in greater detail at www.drawdown.org/explorer.

Assessing deforestation rates

We calculate deforestation using the Hansen et al. tree cover loss data (Hansen et al., 2013; Gibbs et al., 2024). The Hansen et al. approach, which relies on satellite data, assesses loss of tree cover without regard to ecosystem type. To determine ecosystem type, we use maps from Giri et al. to determine mangrove ecosystems using a 50% cutoff to assign a pixel as mangrove, and maps from Global Forest Watch to assess the location of peatlands, also with a 50% cutoff. When a pixel was reported as both mangrove and peatland, we gave the mangrove identification priority.

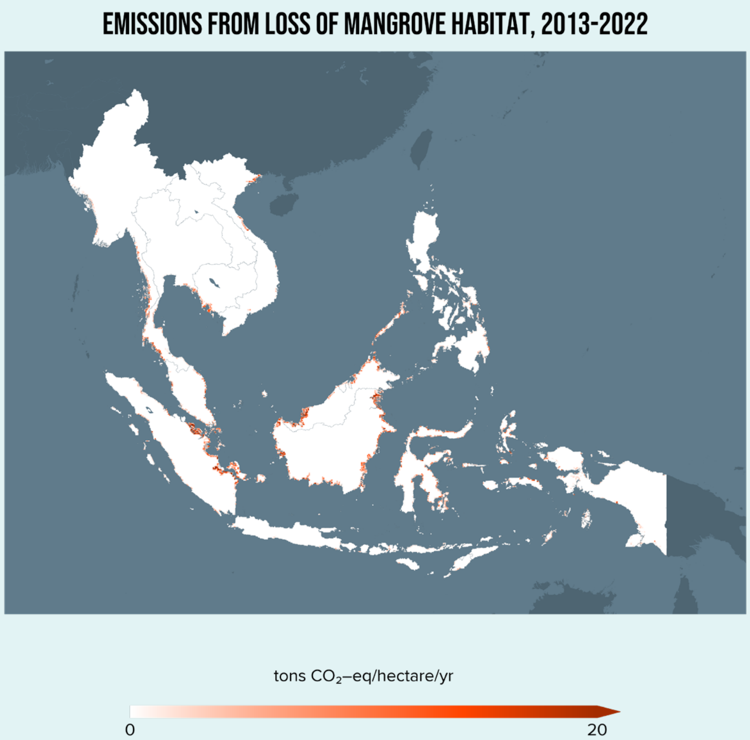

FIGURE 30. *Emissions from the loss of mangroves from 2012 to 2022. We have allocated the emissions beyond mangrove areas for figure legibility. Data sources: Harris et al. (2021); Giri et al. (2010).*

“Hotspots” of deforestation are defined as areas exceeding various thresholds of tree cover loss over a specified time period and are defined at the pixel level. For visualization purposes, heatmaps are produced of the hotspot pixels, and areas of the heatmaps that exceed a threshold are identified as hotspots. Numbers given throughout this report are based on the pixel-level calculations, not the visualizations.

Assessing loss of mangroves and associated carbon flux

Southeast Asia covers just 4–5% of the world's land area, but hosts about one third of the global extent of tropical mangroves.

Mangroves can exist on peatland soils, or on clay or sand (Surahman et al., 2022). Here, we discuss mangrove forests as a single category, regardless of whether they are on peatland soils or on clay or sandy soils. The justification for this is that mangrove forest protection solutions or interventions are independent of the type of soil, while at the same time our calculations of emissions and hotspots are based on soil carbon emissions maps which take into account soil properties at a fine scale (Harris et al., 2021; Gibbs et al., 2024).

The location of mangroves is determined from the Giri et al. dataset. This is a 30-meter-high resolution dataset, which is also used by UNEP. The Hansen et al. forest loss data includes loss of mangrove forests. Following Harris et al., we intersect the Giri et al. dataset with the Hansen data to establish land use change in mangrove forests. Soil carbon data comes from Sanderman et al. (2017), while data related to carbon in woody biomass comes from Spawn et al. (2020). For a detailed discussion of the methods, please see www.drawdown.org/explorer.

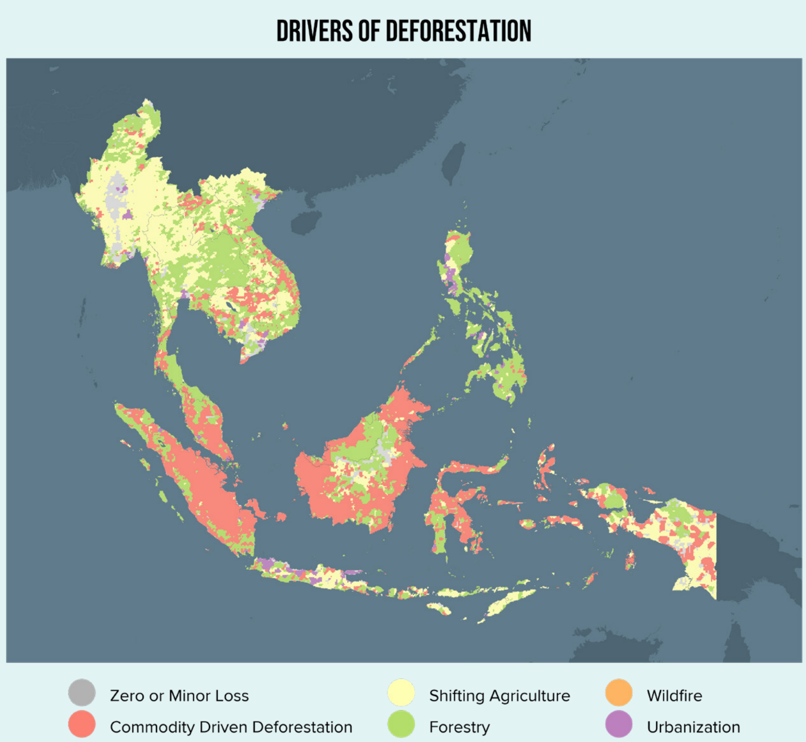

FIGURE 31. *Map of the drivers of deforestation, adapted from Curtis et al. (2018).*

Conversion of mangroves to agriculture, aquaculture, or other development is associated with substantial loss of above- and below-ground carbon following soil disturbance and tree removal during development. Here, we use carbon emissions values associated with conversion of mangrove to aquaculture.

What is driving deforestation?

The dominant source of emissions in Southeast Asia stems from land use change. These land use changes are almost always done for agricultural expansion, tree plantations for timber, or aquaculture. A growing and increasingly affluent population – together with booming global demand for exports such as oil palm, timber, and rubber – is placing significant pressure on the region's forests.

More than 90% of rubber plantations are in Southeast Asia. Rubber is produced from the latex of a tropical tree, and rubber plantations can be difficult to distinguish from natural forests in satellite imagery, making it challenging to identify conversion of forest to rubber trees from space. A majority of natural rubber is produced by smallholders, meaning that their plantations are often below five hectares in size, increasing the challenge of detecting them from satellite imagery (Wang et al., 2023).

Estimated cost of forest protection

We estimated that forest protection costs approximately US$2/t CO_2-eq (Table 3). Data related to the costs of forest protection are limited, and these estimates are uncertain. The costs of forest protection include up-front costs of land acquisition and ongoing costs of management and enforcement. The market price of land reflects the opportunity cost of not using the land for other purposes, such as agriculture or logging. Protecting forests also generates revenue, notably through increased tourism. Costs and revenues vary across regions, depending on the costs of land and enforcement and the potential for tourism.

The cost of land acquisition for ecosystem protection was estimated by Dienerstein et al. (2024), who found a median cost of US$988/ha (range: US$59–6,616/ha), which we amortized over 30 years. Costs of protected area maintenance were estimated at US$9–17/ha/yr (Bruner et al., 2004; Waldron et al., 2020). These estimates reflect the costs of effective enforcement and management, but many existing protected areas do not have adequate funds for effective enforcement (Adams et al., 2019; Barnes et al., 2018; Burner et al., 2004). Tourism revenues directly attributable to forest protection were estimated to be US$43/ha/yr, not including downstream revenues from industries that benefit from increased tourism (Waldron et al., 2020). Inclusion of a tourism multiplier would substantially increase the estimated economic benefits of forest protection.

Table 3. Cost per unit of climate impact (100-yr basis)

Unit: 2023 US$ per ton CO_2-eq	
Median	$2

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PROTECT PEATLANDS

Overview

Peatlands are diverse ecosystems characterized by waterlogged, carbon-rich peat soils consisting of partially decomposed plant material (Figure 32). These tropical wetlands sequester significant amounts of carbon in a small area, but they are often drained and deforested for agriculture and tree plantations.

Peatlands are degraded or destroyed through clearing of vegetation and drainage for agriculture, forestry, peat extraction, or other development. An estimated 600 billion tons of carbon (approximately 2,200 $GtCO_2$-eq) is stored in peatlands globally – twice as much as the carbon stock in all forest biomass (Yu et al., 2010; Pan et al., 2024). Because decomposition occurs very slowly under waterlogged conditions, large amounts of plant material have accumulated in a partially decomposed state over millennia. These carbon-rich ecosystems occupy only 3–4% of land area (Xu et al., 2018; UNEP, 2022). The protection of peatlands is feasible due to their small area and highly impactful due to their carbon density.

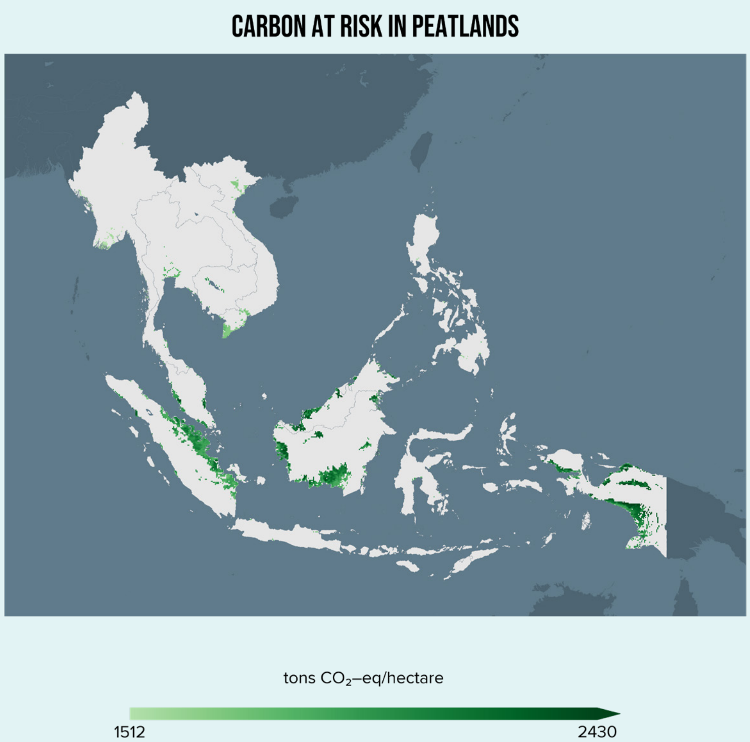

FIGURE 32. *Estimate of carbon at risk from deforestation on peatland soils across Southeast Asia. The carbon at risk, expressed in units of CO_2-eq, is from degradation of woody biomass and 30 years of oxidation of drained soils (see Methods Appendix).*

Southeast Asia contains about half of the world's tropical peatlands. Unfortunately, around 25 million hectares of peatlands in the region have been deforested and drained over the last three decades alone. As of 2021, the Association of Southeast Asian Nations (ASEAN) estimated that only 6% of peatlands in the region remain untouched.

Most peatlands in Southeast Asia are in Indonesia, which has more than 80% of total peatland area. Other major peatland areas are found in Malaysia, Brunei Darussalam, and Thailand, while Vietnam, the Philippines, Cambodia, Laos, and Myanmar contain smaller areas.

About 25 million hectares of peatlands in Southeast Asia have been deforested and drained over the last 30 years. Protecting peatlands has the highest per-hectare emissions savings of any food, agriculture, and land use solutions. Protecting peatlands in Southeast Asia saves three times the carbon, per hectare, of tropical forests on mineral soils. We estimate the net cost of peatland protection is approximately US$17/ha/yr, or approximately US$3 per ton of CO_2-eq avoided.

Peatland Loss and Scope of Emissions

Peatlands are under threat due to agricultural expansion and demand for oil palm, rubber, timber, and soy. The majority of peat swamp forests in Southeast Asia are converted into oil palm and tree plantations (Sasmito et al., 2025).

When peatlands are drained or disturbed, the rate of carbon loss increases sharply as the accumulated organic matter begins decomposing. Removal of overlying vegetation produces additional emissions while also slowing or stopping the rate of carbon uptake. Whereas emissions from vegetation removal occur rapidly following disturbance, peat decomposition and associated emissions can continue for centuries depending on environmental conditions and peat thickness. Peat decomposition after disturbance occurs faster in warmer climates because cold temperatures slow microbial activity.

In addition to peat decomposition, biomass removal, and lost carbon sequestration, peatland disturbance impacts methane and nitrous oxide emissions, as well as carbon loss through waterways (IPCC, 2014; UNEP, 2022). Intact peatlands are a source of methane because of methane-producing microbes, which thrive under waterlogged conditions. However, carbon uptake typically outweighs methane emissions. Leifield et al. (2019) found that intact peatlands are a net carbon sink of 1.65 ± 0.51 tons CO_2-eq per hectare per year in tropical regions after accounting for methane emissions.

When peatlands are logged or drained they become enormously flammable. Fires on peatlands burn up vast amounts of carbon and can spread below the surface, making them difficult to extinguish. For that reason, peatland fires turn one of the Earth's most efficient long-term carbon sinks into a massive short-term emission source. Haze from such fires is hazardous to human health and frequently leads to economic disruptions in the region, as well as school closures.

Emissions and Hotspots

During the study period of 2001 to 2023, deforestation and the draining of peatlands across Southeast Asia emitted on average 577 million tons of CO_2-eq per year. About 286,000 hectares of peatlands underwent landcover change during this period. For this analysis, we estimate that all of the carbon in the above-ground biomass ends up in the atmosphere, in addition to 30 years of emissions of carbon from the soil, which are referred to as committed emissions. (See Methods Appendix for additional details.)

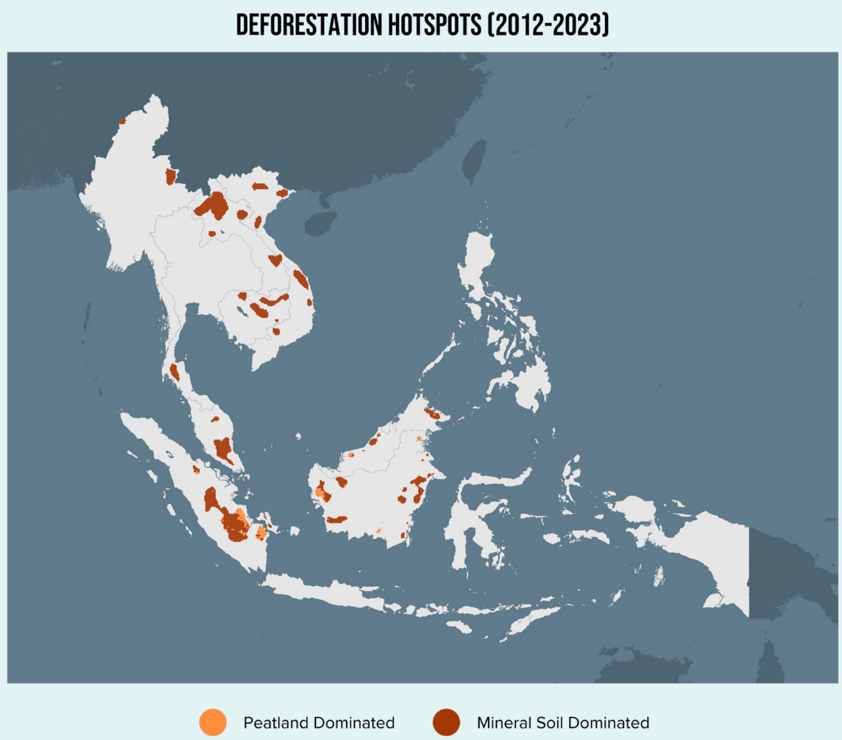

FIGURE 33. *Deforestation hotspots on peatland and mineral soils in Southeast Asia between 2012 and 2023.*

In terms of climate solutions, protecting peatlands has the highest potential emissions savings per hectare – every hectare emitted could save 2,012 tons CO_2-eq emissions. This is three times the emissions savings to be expected from protecting tropical forests on mineral soils.

Protecting Peatlands and Estimated Costs

Patterns of ongoing peatland drainage are poorly understood, but in general, rates of ecosystem disturbance are lower in protected areas and on Indigenous people's lands than they are outside of such areas (Li et al., 2024b; Wolf et al., 2021; Sze et al., 2021).

We estimated that the net cost of peatland protection is approximately US$17/ha/yr, or approximately US$3 per ton of CO_2-eq avoided. Data related to the costs of peatland protection are very limited. These estimates reflect global averages rather than regionally specific values, and often include data not specific to peatlands. The costs of peatland protection include up-front costs of land acquisition and ongoing costs of management and enforcement. The market price of land reflects the opportunity cost of not using the land for other purposes, such as agriculture, forestry, peat extraction, or urban development. Protecting peatlands can also generate revenue through increased tourism. Costs and revenues are highly variable across regions, depending on the costs of land and enforcement and the potential for tourism.

Dienerstein et al. (2024) estimated the initial cost of establishing a protected area for 60 high-biodiversity ecoregions. Amongst the 33 regions that were likely to contain peatlands, the median acquisition cost was US$957/ha, which we amortized over 30 years. Costs of protected area maintenance were estimated to range from US$9–17/ha/yr, though these estimates were not specific to peatlands (Waldron et al., 2020; Bruner et al., 2004).

These estimates reflect the costs of effective enforcement and management, but many existing protected areas do not have adequate funds for effective enforcement (Adams et al., 2019; Barnes et al., 2018; Bruner et al., 2004). Underfunding jeopardizes protected areas' ability to safeguard peatlands and the carbon they store. Waldron et al. (2020) estimated that, across all ecosystems, tourism revenues directly attributable to protected area establishment were US$43 ha/yr, not including downstream revenues from industries that benefit from increased tourism. Inclusion of a tourism multiplier would substantially increase the estimated economic benefits of peatland protection.

THE MARKET PRICE OF LAND REFLECTS THE OPPORTUNITY COST OF NOT USING THE LAND FOR OTHER PURPOSES, SUCH AS AGRICULTURE, FORESTRY, PEAT EXTRACTION, OR URBAN DEVELOPMENT. PROTECTING PEATLANDS CAN ALSO GENERATE REVENUE THROUGH INCREASED TOURISM.

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IMPROVE NUTRIENT MANAGEMENT

Overview

Improving nutrient management involves reducing excessive nitrogen use on croplands. Nitrogen is critical for crop production and is added to croplands through the use of fertilizers and through microbial activity. However, too much nitrogen is used in some regions. Some of the excess nitrogen that cannot be used quickly enough by crops is emitted to the atmosphere as nitrous oxide, a potent greenhouse gas. Using the right amount and right type of nutrients at the right time and right place can reduce nitrous oxide emissions by ensuring that the nitrogen gets taken up by crops instead of being emitted as nitrous oxide.

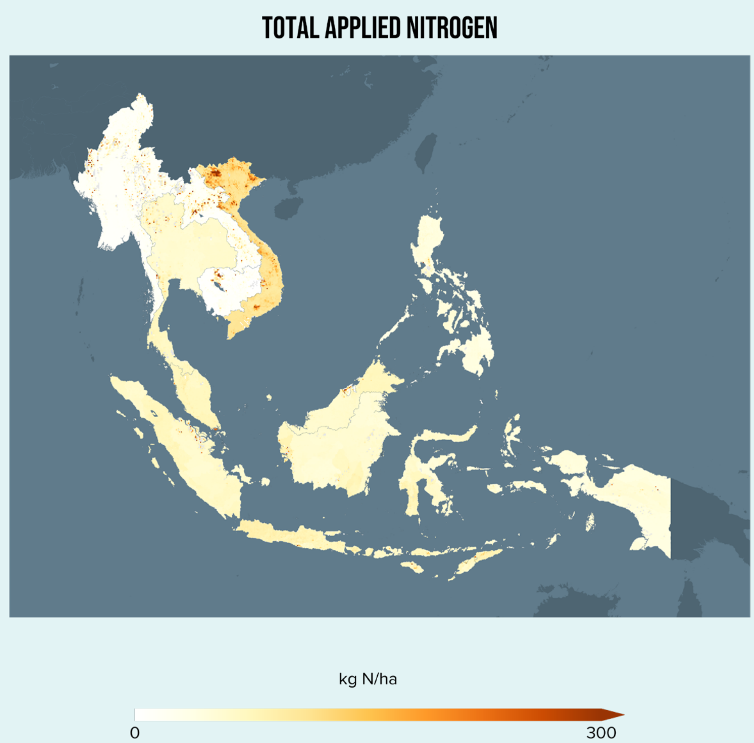

FIGURE 34. *Estimated rates of fertilizer use across Southeast Asia. The excessive use of nitrogen fertilizers and manure are responsible for much of the nitrous oxide emissions we see today. But patterns of fertilizer use are highly variable across Southeast Asia, depending on the crops and countries in question. Data based on Gerber et al., Project Drawdown.*

Agriculture is the dominant source of human-caused emissions of nitrous oxide (Tian et al., 2020). Nitrous oxide emissions can be reduced by using the right rate and the right type of fertilizer at the right time and in the right place. Each of these four principles (right rate, right type, right time, and right place) aims to increase nutrient use efficiency, which refers to the proportion of applied nitrogen that is used by the crop. Improved nutrient management is often a win-win for the farmer and the environment, as it reduces fertilizer costs while also reducing nitrous oxide emissions.

Nitrogen is critical for plant growth, but plants only use nitrogen in certain chemical forms. Plant-available nitrogen is typically added to croplands in the form of synthetic fertilizers such as urea, ammonium nitrate, or anhydrous ammonia; organic fertilizers like manure or compost; or by incorporating legume crops, which host nitrogen-fixing microbes. Ideally, all nitrogen applied to croplands would be taken up by crops and used to produce food. If more nitrogen is applied than the crops can take up, however, the excess nitrogen can be quickly transformed and lost to the environment in other forms, including as nitrous oxide through microbial processes called denitrification and nitrification.

How are improved nutrient management principles implemented in practice? Most importantly, the total rate (or amount) of nitrogen applied should be reduced to match the crop's needs in areas where nitrogen is currently overapplied. Implementing the other three principles can take a variety of forms. For example, fertilizing just prior to planting instead of after the previous season's harvest better matches the timing of nitrogen addition to the timing of plant uptake, reducing opportunities for nitrogen to be lost to the environment as nitrous oxide before the crop is planted. Certain types of fertilizers are better suited for maximizing plant uptake, such as extended-release fertilizers that allow the crop to steadily absorb nutrients over the course of several weeks or longer. Other techniques can improve the placement of fertilizers, such as banding, in which fertilizers are applied in concentrated bands close to the plant roots instead of being spread evenly across the soil surface. Although these are diverse practices, each ultimately decreases the amount of excess nitrogen that can be lost as nitrous oxide.

Nutrient management in paddy rice has very different emissions impacts, so it is excluded from this solution and addressed in the Improve Rice Production topical chapter.

For this solution, we estimated a target rate of nitrogen application for major crops as the 20th percentile of a range of application rates that won't adversely impact yields. We calculate this by assessing nitrogen use efficiency (NUE) in areas where yields are near a realistic ceiling. Excess nitrogen was defined as the amount of nitrogen applied beyond the target rate.[10] Our emissions estimates include nitrous oxide from croplands, fertilizer runoff, and fertilizer volatilization. They do not include emissions from fertilizer manufacturing and we excluded nutrient management on pastures from this solution due to data limitations.

10 Visit www.drawdown.org/explorer to access the Drawdown Explorer methodology for additional details.

Reducing Nutrient Management Emissions

Improving nutrient management involves reducing excessive nitrogen fertilizer use on croplands. Some farm fields in Southeast Asia use more nitrogen fertilizers than is necessary to achieve the same level of crop yields.

Across all non-rice farm fields in Southeast Asia, excess nitrogen fertilizers lead to 53 million tons of CO_2-eq emissions per year. This excess application occurs on 88 million hectares of land. Hotspots of emissions from nutrient management were focused in Thailand, Indonesia, and Vietnam (Figure 35).

HOTSPOTS FOR NUTRIENT MANAGEMENT

FIGURE 35. *Hotspots of nutrient management solutions.*

We find that curtailing fertilizer applications to ensure they were used at the right time and place could reduce nitrous oxide emissions by 11 million tons, without compromising crop yields. Focusing nutrient management on 20% of cropland area could yield 80% of the emissions savings potential.

Estimated Costs

Improving nutrient management typically reduces fertilizer costs while maintaining or increasing yields, resulting in a net financial benefit to the producer. Gu et al. (2023) found that a 21% reduction in global nitrogen use would be economically beneficial, notably after accounting for increased fertilizer use in places that do not currently have adequate access.

Using data from their study, we evaluated the average cost of reduced nitrogen application considering the following nutrient management practices: increased use of high-efficiency fertilizers, organic fertilizers, and/or legumes; optimizing fertilizer rates; altering the timing and/or placement of fertilizer applications; and use of buffer zones. Implementation costs depend on the strategy used to improve nutrient management. For example, optimizing fertilizer rates requires soil testing and the ability to apply different fertilizer rates to different parts of a field. Improving timing can involve applying fertilizers at two different times during the season, which increases labor and equipment operation costs. Furthermore, planting legumes incurs seed purchase and planting costs.

Gu et al. (2023) estimated that annual reductions of 42 Mt of nitrogen were achievable globally using these practices, providing total fertilizer savings of US$37.2 billion and requiring implementation costs of US$15.9 billion, adjusted for inflation to 2023. A one ton reduction in excess nitrogen application, therefore, was estimated to provide an average of US$507.80 of net cost savings, corresponding to a savings of US$85.21 per t CO_2-eq of emissions reductions (Table 4).

TABLE 4. *Cost per unit of climate impact, 100-yr basis*

Unit: 2023 US$ per ton CO_2-eq	
Mean	-$85.21

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IMPROVE RICE PRODUCTION

Overview

In 2022, farmers in Southeast Asia produced 25% of global rice supplies. Rice fields are a significant source of methane and nitrous oxide emissions. This important crop is responsible for almost 300 million tons of CO_2-eq emissions in the region annually.

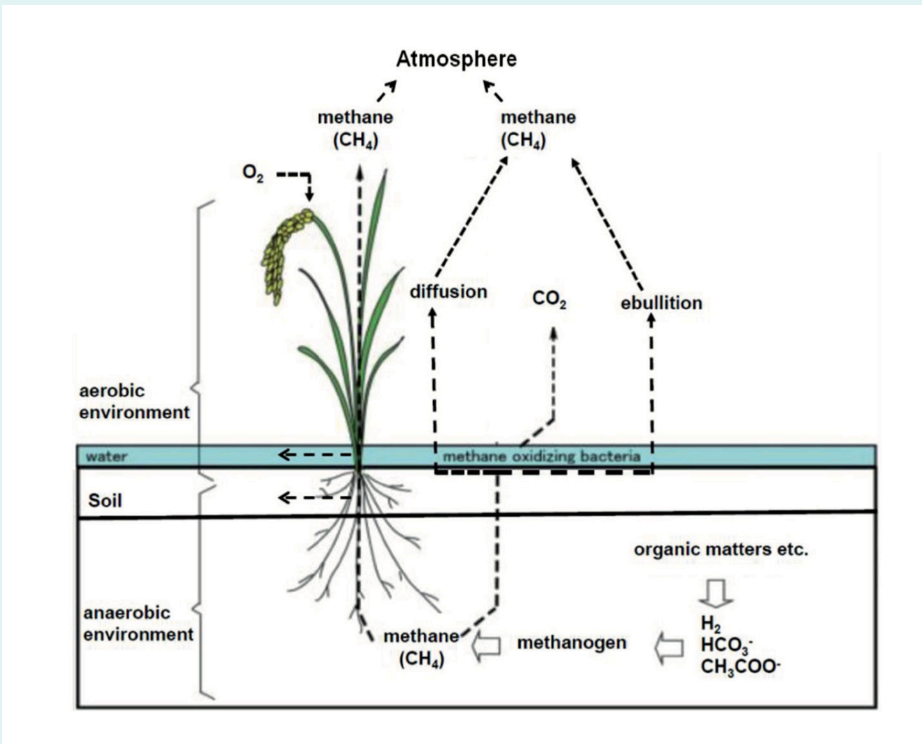

FIGURE 36. *Pathways of the production of methane, from Methane Cycling in Paddy Field: A Global Warming Issue (Rahman, M. M., & Yamamoto, A., 2020).*

Rice production has higher emissions than most crops, accounting for 9% of all anthropogenic methane, and 10% of cropland nitrous oxide (Wang et al., 2020). Methane emissions from global rice production are 0.8–1.0 Gt CO_2-eq/yr, and growing at 0.4% annually (Jackson et al., 2024; Nabuurs et al., 2022).

Most rice production takes place in flooded fields called paddies, where anaerobic conditions trigger methane emissions. This solution includes two related practices that each reduce emissions from paddy rice production – non-continuous flooding and nutrient management. Non-continuous flooding is a water management technique that reduces the amount of time that rice paddy soils spend under fully saturated conditions, thereby reducing methane emissions. Unfortunately, non-continuous flooding increases nitrous oxide emissions. Nutrient management helps to address this challenge by controlling the timing, amount, and type of fertilization to maximize plant uptake and minimize nitrous oxide emissions.

Improving rice production is an “emergency brake” climate solution. It has a disproportionately rapid impact after implementation because it reduces the short-lived climate pollutant methane through non-continuous flooding.

Non-continuous Flooding

There is high consensus on the effectiveness and potential of non-continuous flooding and nutrient management (Jiang et al., 2019; Zhang et al., 2023; Nabuurs et al., 2022; Qian et al., 2023; Bo et al., 2022). The methane reduction and associated nitrous oxide increase from non-continuous flooding are described in detail, with formulas provided, in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Hergoualc’h et al., 2019). Bo et al. (2022) calculate that 76% of global rice paddies are suitable to switch to non-continuous flooding without reducing yields. This would reduce methane and nitrous oxide emissions from rice production by 47%.

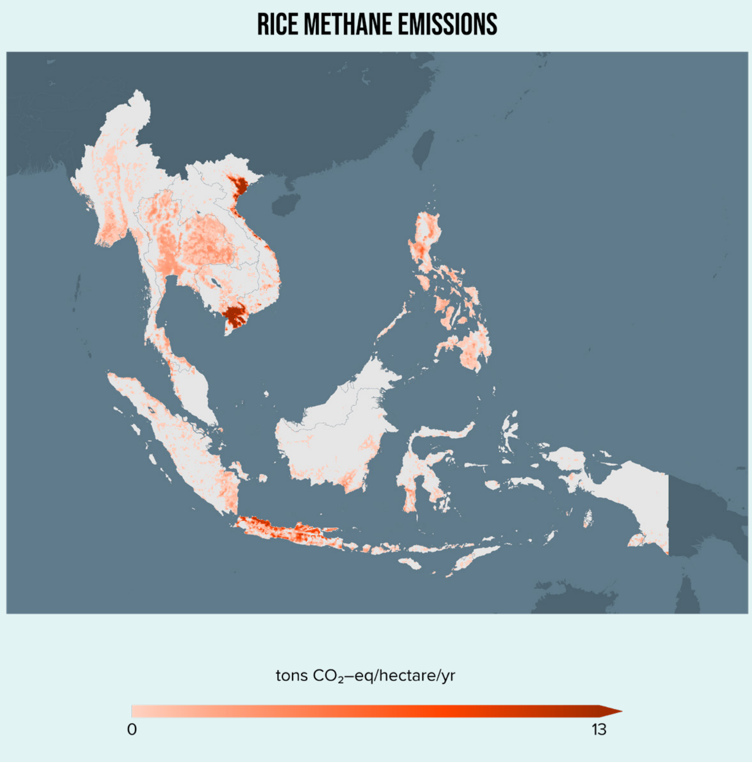

FIGURE 37. *Rice methane emissions across Southeast Asia in 2020.*

There are barriers to adoption. Not all paddy rice is suitable for improved water management, and under certain conditions yield reductions are possible but undesirable (Bo et al., 2022). Other challenges include water access, coordinating water usage between multiple users, and ownership of water pumps (Nabuurs et al., 2022).

However, field studies across South and Southeast Asia have shown that AWD can typically reduce irrigation requirements by 20-30% compared to conventional flooded systems without adversely affecting rice yield or grain quality (Suwanmaneepong et al., 2023; Carrijo et al., 2017). This reduction in water usage alleviates pressure on water resources in drought-prone areas (Alauddin et al., 2020).

Globally, rice production uses about 40% of all global irrigation water. However, adoption of non-continuous flooding on 76% of fields could reduce rice irrigation needs by 25% (Bo et al., 2022).

Emissions and Hotspots

Across Southeast Asia, farming rice generates almost 300 million tons of CO_2-eq emissions. These emissions are largely concentrated within Vietnam, Indonesia, and Thailand.

In Figure 38, we show hotspots of potential for implementing improved rice cultivation. These areas have at least 1% of the land cultivated within the pixel and were significant sources of emissions in 2020. The map in Figure 38 represents 10% of rice-growing areas, but 50% of addressable emissions.

Vietnam's rice fields have the highest emissions per hectare – 14 tons CO_2-eq per hectare, which is twice the regional average. This is due to the prevalence of continuous flooding and triple cropping within the primary rice-growing areas in Vietnam – the Red River delta in the north and the Mekong River delta in the south. Rice production within these deltas drive 10% of global rice methane emissions, yet Vietnam produces just 5% of global rice (Carlson et al., 2017). Improving rice cultivation – primarily with non-continuous flooding – on 20% of Vietnam's fields could reduce emissions by 60%.

Method Details

Methane reduction

Per-hectare methane emissions were calculated using the IPCC methodology (Ogle et al., 2019). To develop regional emissions per rice harvest, we multiplied standard regional daily baseline emissions by standard cultivation period lengths and multiplied by the mean scaling factor for non-continuous flooding systems. However, the total number of rice harvests per year ranges from one to three. Carlson et al. (2017) report a global figure of harvests on rice fields – 42% of rice fields are harvested once a year, 50% are harvested twice, and 8% are harvested three times. We used this to develop a weighted average methane emissions figure for each region. Results are shown in Table 5.

Current uptake of non-continuous flooding

We used data from Cao et al. (in review, with preprint available at researchsquare and data available at figshare) to assess current uptake of non-continuous flooding solutions. We combined single-flooding and multiple-flooding practices and assessed their potential as AWD management using data from Bo et al. (2022). The Cao et al. data only estimates uptake at the national level – as a result, there is some spatial uncertainty in our maps. Consequently, we only present results based on a smoothing algorithm for assessing areas of maximum potential.

Nitrous oxide reduction

Using data from Adalibieke et al. (2024) and Gerber et al. (2024), we calculated the current country-level rate of nitrogen application per hectare and a "target" rate reflecting improved efficiency through nutrient management.

In non-continuously flooded systems, nitrous oxide emissions are 1.66 times higher per ton of nitrogen applied (Hergoualc'h et al., 2019). Using the different emissions factors, we calculated total nitrous oxide emissions for 1) flooded rice with current nitrogen application rates and 2) non-continuously flooded rice with target nitrogen application rates.

The combined effectiveness of non-continuous flooding and nutrient management for each country with over 100,000 hectares of rice is shown in Table 5. Note that these practices are not necessarily additive.

TABLE 5. *Combined effectiveness at reducing emissions, by country, for non-continuous flooding with nutrient management*

Unit: t CO_2-eq 100-year basis (with 20-year basis in parentheses) per hectare installed per year; for nitrous oxide, the values for 20- and 100-year emissions are the same			
Country	**Methane reduction, tCO_2-eq/ha/yr**	**Nitrous oxide reduction, tCO_2-eq/ha/yr**	**Combined effectiveness tCO_2-eq/ha/yr**
Cambodia	2.13 (6.21)	0.01 (0.01)	2.15 (6.22)
Indonesia	2.13 (6.21)	0.11 (.011)	2.24 (6.31)
Laos	2.13 (6.21)	0.02 (0.02)	2.15 (6.23)
Malaysia	2.13 (6.21)	-0.01 (-0.01)	2.13 (6.20)
Myanmar	2.13 (6.21)	0.04 (0.04)	2.17 (6.25)
Philippines	2.13 (6.21)	0.00 (0.00)	2.14 (6.21)
Thailand	2.13 (6.21)	-0.03 (-0.03)	2.10 (6.18)
Vietnam	2.13 (6.21)	0.00 (0.00)	2.13 (6.20)

Estimated Cost

Conventional paddy rice. For conventional paddy rice, the initial cost is assumed to be US$0, as many millions of hectares of paddies are already in place. Regional per-hectare average profits in US$ from Damania et al. (2024) are used as the source for net profit per year. Because initial cost per hectare is US$0, net cost per hectare is the same as per-hectare annual profit.

TABLE 6. *Net cost and profit of conventional paddy rice by region*

Unit: 2023 US$			
Region	**Initial cost $/ha**	**Profit $/ha/yr**	**Net cost $/ha/yr**
South Asia	$0.00	$488.85	-$488.85
Southeast Asia	$0.00	$322.13	-$322.13

Non-continuous flooding. The initial cost is assumed to be US$0, as no new inputs or changes to paddy infrastructure are required in most cases. Median impact on net profit is an increase of 17% based on nine data points from seven sources. National results are shown in Table 5.

Nutrient management. The initial cost is assumed to be US$0, since in many cases nutrient management begins with reducing the over-application of fertilizer. Here, we use the mean value from Gu et al. (2023), a savings of US$507.80 per ton of nitrogen. Our national-level data on over-application of nitrogen is used to calculate savings per hectare. Regional results shown in Table 6.

Combined net profit per hectare

Net profit per hectare thus varies by country, with regional variables and some country-specific variables contributing.

Net cost compared to conventional paddy rice

Net cost of improved rice production compared to conventional rice production varies by country. National results are shown in Table 7.

TABLE 7. *Net cost and profit of non-continuous flooding with nutrient management by country*

Unit: US$ (2023)/ha/yr					
Country	Initial cost $/ha (non-continuous flooding and nutrient management)	Profit $/ha/yr (non-continuous flooding and nutrient management)	Net cost $/ha/yr (non-continuous flooding and nutrient management)	Net cost $/ha (non-continuous flooding and nutrient management)	$/ton CO_2-eq (non-continuous flooding and nutrient management)
Cambodia	$0.00	$377.81	-$377.81	-$55.68	-$8.95
Indonesia	$0.00	$382.39	-$382.39	-$60.26	-$9.54
Laos	$0.00	$377.04	-$377.04	-$54.91	-$8.82
Malaysia	$0.00	$401.26	-$401.26	-$79.13	-$12.76
Myanmar	$0.00	$380.74	-$380.74	-$58.61	-$9.38
Philippines	$0.00	$399.51	-$399.51	-$77.38	-$12.46
Thailand	$0.00	$407.70	-$407.70	-$85.57	-$13.86
Vietnam	$0.00	$416.68	-$416.68	-$94.55	-$15.25

Cost per unit climate impact

Cost per ton CO_2-eq varies by country. National results are shown in Table 7. The global weighted average is -US$15.03/ton CO_2-eq. Note that this cost is the same for both 100- and 20-year results.

TABLE 8. *Weighted average cost per unit climate impact*

Unit: 2023 US$ per ton CO_2-eq	
Weighted average	-$15.03

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METHODS APPENDIX

Overview

In this appendix, we present some method details and references.

Methods of Hotspot Calculations

Hotspots of solutions and emissions potential

Hotspots are assessed by creating solution "heatmaps," where a pixel is identified as part of a hotspot by summing the solution opportunities within an approximately 80 kilometer radius (using a Gaussian smoothing kernel with sigma = 4 pixels, where each pixel is nominally 10 kilometers). Then, a cutoff for "hotspots" within the heatmap are chosen such that they encompass the same total solution potential as the value obtained by summing the solution potential on the 20% of area with the greatest solution potential intensity.

The intent of this algorithm is that an isolated pixel of very high solution potential may not be included in a hotspot, whereas a cluster of pixels of moderate solution potential may be included in a hotspot. We note that hotspots identified in this way are for visualization purposes. Calculations used to quantify total hectares of solution pixels are calculated without smoothing on a pixel-by-pixel manner.

Hotspots of deforestation

Hotspots of deforestation are calculated in a different way to allow comparison across decades. Here, we limited the calculations to areas with at least 25% forested area, and increased the smoothing radius to allow for more overlap in the visualization.

Emissions Associated with Deforestation on Mineral Soils

We used methods consistent with those developed for the Drawdown Explorer. Our method is notable in that we use a committed flux approach. These methods have been externally reviewed, and additional details can be located at https://drawdown.org/explorer/protect-forests.

Emissions Associated with Loss of Mangroves

We used methods consistent with those developed for the Drawdown Explorer. We use a committed flux approach and assume that land use subsequent to mangrove clearing is consistent with aquaculture. These methods have been externally reviewed, and additional details can be located at https://drawdown.org/explorer.

Emissions Associated with Loss of Peatlands

We used methods consistent with those developed for the Drawdown Explorer. We use a committed flux approach and assume that deforested peatland leads to drainage. We account for 30 years of flux from oxidizing peat. These methods have been externally reviewed, and additional details can be located at https://drawdown.org/explorer.