

# Tradeoffs and synergies for agriculture and environmental outcomes in the tropics\*

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Prepared for submission to *Review of Environmental Economics and Policy*

**JEL codes:** Q15; Q01; Q56

## Abstract

Global population is projected to continue increasing until 2100. Even in the absence of increasing incomes, feeding a growing population will require more land, more machinery, more agricultural inputs, and continued innovation in agricultural technology. The relationship between increased agricultural production and environmental degradation is a central challenge to human well-being. This article compiles available evidence on the relationship between agriculture and the environment, focusing on the tropics, where potential tradeoffs between food production and environmental quality are particularly acute because much larger shares of the population depend upon agriculture for work and subsistence. While our main focus is on land use, where applicable we also touch on associated environmental services, such as soil and air quality and attempt to catalog policies that highlight synergies and tradeoffs between agricultural livelihoods and environmental quality.

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\*Acknowledgment: We are especially grateful to Audrey Ruel-Gauthier for excellent research assistance.

## Introduction

Global population is currently 8 billion, projected to increase by 34% by 2050 and plateau at 10.9 billion by 2100 (UN 2022). Feeding a growing population presents numerous challenges, including the possible need to expand land under agriculture at the expense of tropical forest and to increase the intensity of agricultural input use. Expanding farm area could generate water-contaminating runoff,  $CO_2$  and methane emissions, and the loss of biodiversity and soil carbon. A number of policy challenges affect this trade-off between agriculture and the environment. Climate change makes future food supply more uncertain. Enhanced agricultural technologies are changing the geography and environmental costs of food production. Global trade has trended towards greater integration, fundamentally changing where food is produced.

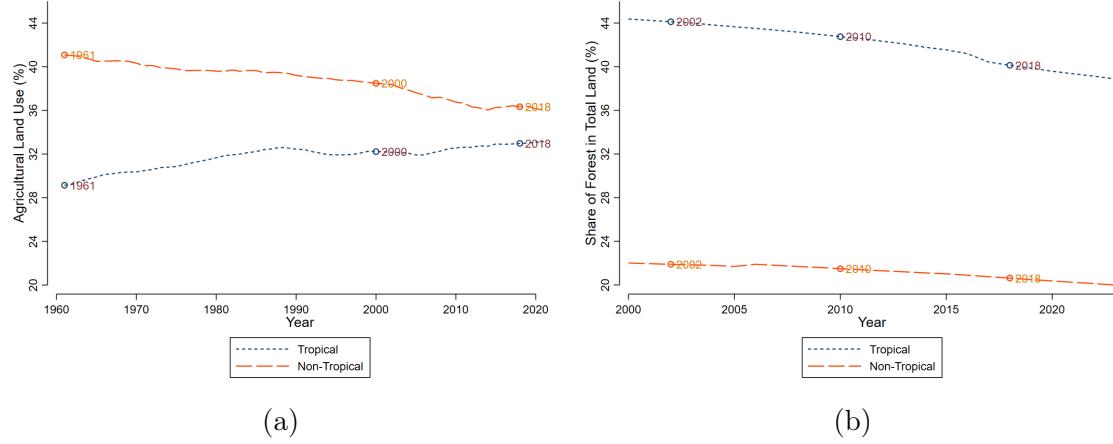
Given these complexities, the relationship between increased agricultural production and environmental degradation is a central challenge to human well-being. Will feeding the world leave it with less forest, contaminated air and water, and decreased biodiversity? Are there pathways to food security that also conserve or improve environmental quality? This article compiles recent evidence on the relationship between agriculture and the environment, focusing on the tropics, where potential tradeoffs between food production and environmental quality are particularly acute because much larger shares of the population depend upon agriculture for work and subsistence. While land use is our primary metric of environmental impact, where possible we also touch on associated ecosystem services, such as soil and air quality. Land use change features prominently because the conversion of forest to crops represents an exchange of agricultural production for environmental services. It is also the case that with the spread of large scale satellite-based metrics of forest, deforestation is one of the most frequently measured environmental outcomes in the literature.

Recent remote sensing estimates show that forest area has decreased by 2.4% between 2000 and 2020 (a loss of over 1M km<sup>2</sup>) and agricultural land area has increased by 11.5% (an area of 1.25M km<sup>2</sup>) (Potapov et al. 2022). Figure 1<sup>1</sup> shows the evolution of agricultural land use over time for tropical and non-tropical countries using administrative data from the Food and Agriculture Organization (FAO) and remotely sensed measures of deforestation from Global Forest Watch. While agricultural land shares in non-tropical countries have declined over the last half-century, tropical agricultural land shares have climbed. Forest cover has decreased in these same countries, while remaining constant in non-tropical areas.

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<sup>1</sup>All figures use FAOStat (2024) data except where noted. For each data series, countries with more than 5 years of missing data were removed. Countries are classified as tropical or non-tropical as in Appendix A. We note final sample sizes in the caption of each figure.

Figure 1: Evolution of agricultural and forest land use



Note: (a) illustrates the evolution of agricultural land use as a percentage of each country's total land area, from 1961 to 2021. Final sample: 158 countries (62 non-tropical, 96 tropical). (b) shows the evolution of the forest share as a percentage of each country's total land area from 2000 to 2023 and includes data from Global Forest Watch (2024). The forest share for each year and country was calculated using the baseline forest area in hectares in 2000, adjusted annually by subtracting deforestation (in hectares). Final sample: 180 countries (94 tropical, 86 non-tropical).

Estimates from 2015 indicate that forests are mostly replaced by cropland and pasture (Tyukavina et al. 2015). The simple comparison between agricultural and cropland area suggests that increases in the former come at the expense of the latter in many parts of the world, with the highest areas of net forest loss in South America ( $440,000 \text{ km}^2$ ) and Africa ( $320,000 \text{ km}^2$ ), and the largest areas of agricultural expansion in Africa ( $470,000 \text{ km}^2$ ) followed by South America ( $340,000 \text{ km}^2$ ) (Potapov et al. 2022).

Our central contribution is to provide a deep dive into food production as a cause of land-use change in low- and middle-income countries, highlighting the recent rapid expansion of causal evidence in this space. Our work complements a number of existing reviews that focus broadly on the causes and consequences of land-use change around the world. Barbier (2001) summarizes the economics of deforestation and land use as of 2001. Jayachandran (2022) examines how economic development influences the environment, dedicating some space to the agricultural productivity channel. Villoria, Byerlee, and Stevenson (2014) examine the effects of agricultural technology on deforestation, and García (2020) provides a report focused on the environmental effects of agricultural intensification on various environmental outcomes. Most recently, Balboni et al. (2023) presents a broad review of economic theory and empirical analysis associated with tropical deforestation. This work covers some aspects of land use change associated with agriculture, but does not highlight environmental effects of the broad suite of policies intended to increase food production.

Finally, Busch and Ferretti-Gallon (2017) and Busch and Ferretti-Gallon (2023) conduct

a meta-analysis of drivers of land-use change. By contrast, our approach is a narrative review (Greenhalgh, Thorne, and Malterud 2018). We provide summary along with interpretation and critique, including assessments of internal and external validity, and we frame our analysis with economic theory. We consider our analysis to complement the drivers approach, which demonstrates, for example, that lower slope and fertile land influence deforestation. While this can be helpful in targeting policies towards high-risk areas, it does not clarify the tradeoffs inherent in the design of such policies, nor does it assess whether interventions also improved food production.

The next section presents a basic theoretical model and contextual descriptive evidence, which we then link to recent micro-based findings. The subsequent section shifts to the global context, focusing on macroeconomic and trade-related evidence. Finally, we conclude by cataloging interventions that generate positive agricultural production and environmental outcomes, highlighting gaps in the literature, and outlining key areas for future research based on our review.

## Organizing framework

Our discussion begins with the canonical Von Thünen model of land rent, in which land is allocated to the use with the highest rent. This is a standard approach in land economics, and it has frequently been used to give context to the feedback between deforestation-reducing policies and agricultural production (Angelsen 2010). In this paper, we consider the opposite dynamic – how agricultural output can be increased while conserving or restoring natural landscapes. The land rent model can accommodate a number of land uses, but to fix ideas we will use three: intensive agriculture, extensive agriculture, and forests. Further, this model is preferable to some other canonical models of forest loss (reviewed in Balboni et al. (2023)) because the majority of tropical deforestation occurs not to harvest trees, but rather to plant new crops, graze animals, and expand urban boundaries (Jayathilake et al. 2021).

Figure 2 shows the simplest schematic of these relationships. Each of the rent curves are downward sloping, following from the assumption that there are non-zero costs of transporting goods to the market at the city center (the graph's origin). The hierarchy of land uses has the highest rents coming from intensive agriculture ( $R^{ai}$ ) up to point  $A^*$ , then extensive agriculture ( $R^{ae}$ ) up to  $\bar{F}$ , and finally forest ( $R^f$ ). The forest frontier exists at the point at which extensive agriculture and forest yield the same level of rent. Private forest rents include forest use value (timber, local ecosystem services, non-timber forest products) and future development value. The model easily extends to include broader forest ecosystem values as an externality, not directly valued by the decision-making landholder.

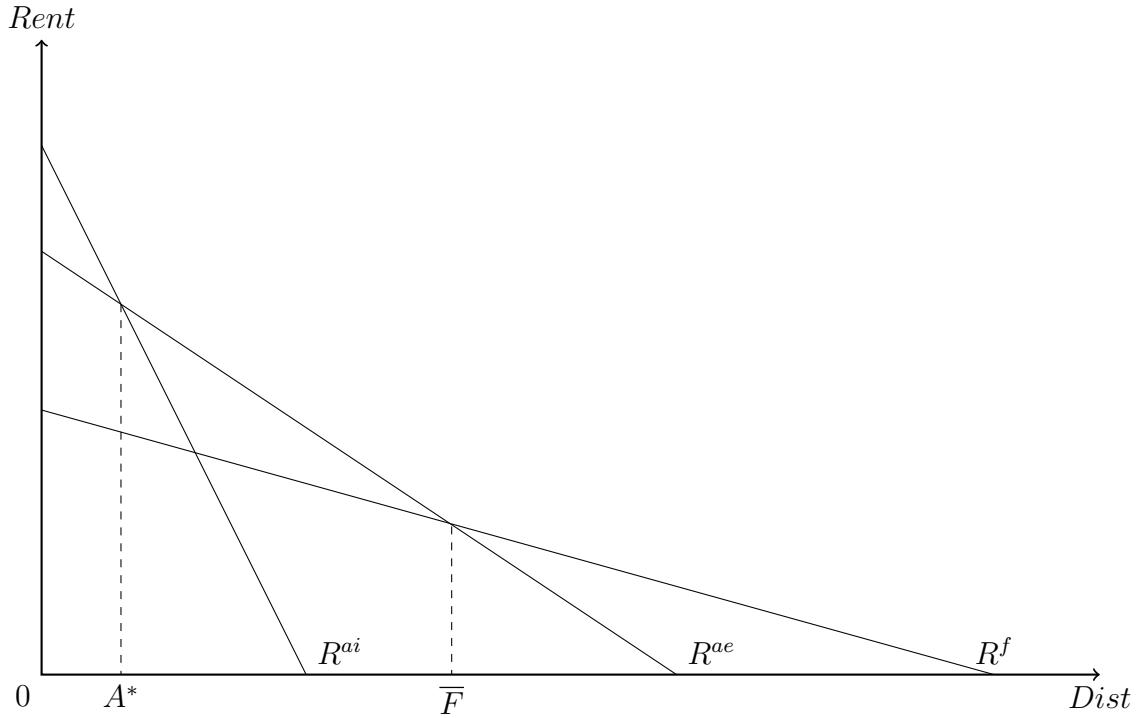


Figure 2: Simple land rent model

Increases in agricultural production result from changes in output or input prices (including the wage and agricultural credit), technological progress, reductions in transport costs, and institutional changes which improve certainty around future agricultural rents (e.g., improved tenure rights). In the simplest version of this model, where frictions in labor or credit markets are absent, we highlight a prediction of the model that is particularly relevant to the tropics.

To begin, take the case of former colonies situated in tropical regions, where colonizing countries were concerned about local land occupation and border control. Colonial regimes enacted policies that aimed to settle the population in the interior regions of these countries. Importantly, resettlement incentives primarily encouraged extensive agriculture. In our framework, this can be understood as having a much flatter extensive agricultural  $R^{ae}$  rent gradient than that of intensive agriculture  $R^{ai}$ . As a result, population growth and the expansion of new cities in the country's interior cleared land for extensive agriculture (Pichon 1997; Barbier 2004).

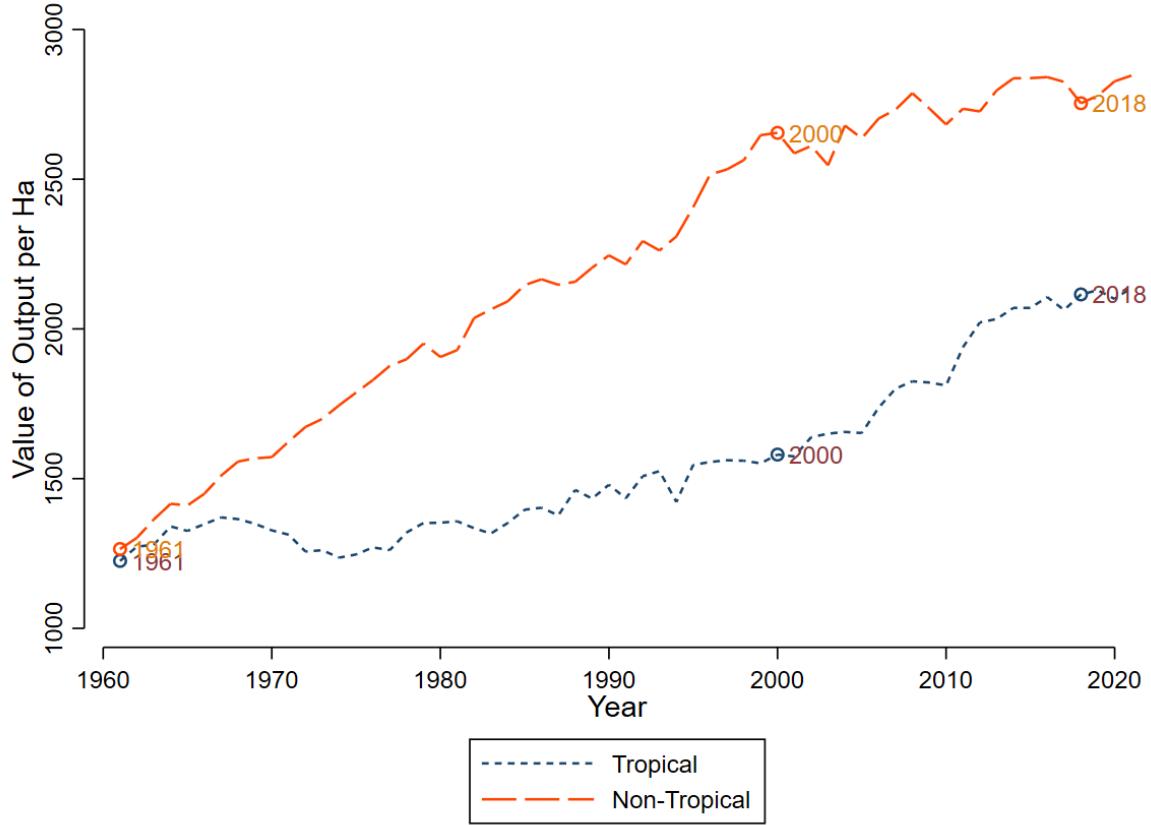
Now suppose a scenario where the Green Revolution, marked by the introduction of new technology and the advancement of intensive agriculture, encounters a substantial amount of preexisting cleared land. The curve  $R^{ai}$  flattens significantly, raising intensive agricultural value further out from the origin, while agricultural extensification was already profitable

such that even under the flatter  $R^{ai}$  curve,  $A^* \leq \bar{F}$ . In this case, innovation has the potential to induce more efficient land use, resulting in improved production through yield gains, without the need to expand deforestation. Historical patterns of extensification create low-productivity agricultural zones that can act as a buffer to absorb continuous improvements in  $R^{ai}$  without altering the extent of forests.

On the other hand, in areas where extensive agriculture is not prevalent, improvements in the prospects of intensive agriculture can lead to a distinct outcome. In these areas, yield gains increase agricultural profitability compared to forested areas and can thus lead to additional deforestation. This phenomenon is commonly known as “Jevons paradox”. The role of history is therefore pivotal in understanding the connection between agricultural productivity and deforestation, and whether the phenomenon of the “Jevons paradox” emerges (Phalan et al. 2016).

From Figure 1, we know the area in agriculture has been decreasing in non-tropical and increasing in tropical countries. Figure 3 shows that land productivity, measured in agricultural output per hectare, increased more quickly for non-tropical versus tropical countries up until 2000. After 2000, non-tropical agricultural productivity flattens and tropical productivity inflects upwards.

Figure 3: Evolution of output value per ha of agricultural land

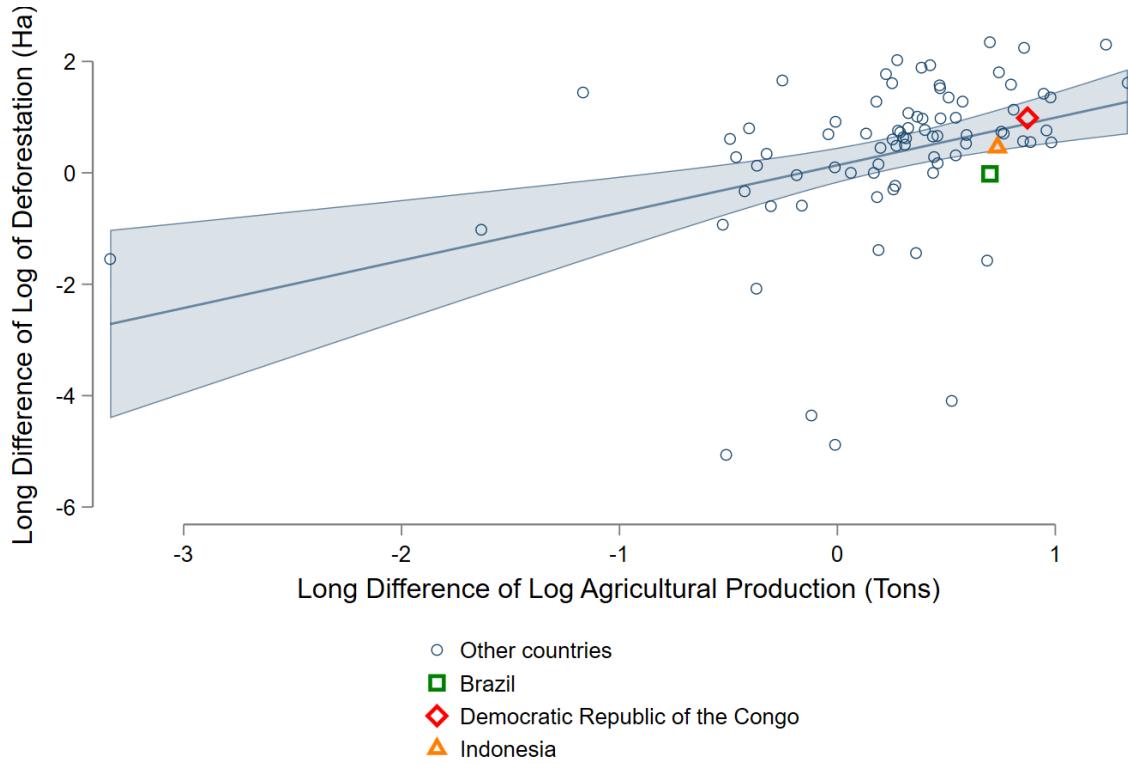


Note: Output value is measured by gross production value in constant 2014-2016 thousand US dollars, while agricultural land is measured in thousands of hectares. Output value per hectare is expressed in dollars/ha. Final sample: 115 countries (48 non-tropical, 67 tropical).

These figures taken together suggest that growth in non-tropical, intensive agricultural technologies enabled smaller land footprints with greater productivity between 1960-2000. These productivity gains seem not to have led to a Jevons paradox in this context. Productivity gains have not been realized at the same rate in the tropics, at least on average.

Figure 4 correlates increases in agricultural production and tropical forest loss. The general relationship is positive. However, there is a wide range of realized deforestation outcomes at all levels of agricultural productivity change, suggesting an underlying mix of intensive and extensive agricultural growth. The section on global context below discusses the role of international trade.

Figure 4: Relationship Between Long Difference in Log of Deforestation and Log of Agricultural Production for Tropical Countries (2001-2019)



Note: Difference in the log of deforestation (measured in hectares) from 2001 to 2019, calculated as the log of deforestation in 2019 minus the log of deforestation in 2001, and the difference in the log of agricultural production (measured in tons) from 2001 to 2019, calculated as the log of agricultural production in 2019 minus the log of agricultural production in 2001. Deforestation data from Global Forest Watch ([2024](#)). Final sample: 83 tropical countries. The shaded area represents the 95% confidence interval.

Climate change and a better understanding of ecosystem services have introduced an additional dimension to forest value through carbon stocks or impact on rainfall. In the case where these services are priced into land rents, they shift the  $R^f$  curve upward. The opportunity cost of agriculture increases, reducing  $\bar{F}$ . Pricing the environmental value of forest leads to greater forest growth in low-productivity agriculture areas, typically associated with extensive technologies.

The framework is also useful for assessing the impact of policy interventions. Extensions to the model can also accommodate credit constraints or other market frictions (Angelsen [2007](#)). In the following sections, we apply this framework to understand how policy tools and changes in the economic context can affect productivity, deforestation, and environmental externalities.

## Evidence from micro economic studies

This section presents evidence on the impacts of specific policies intended to increase agricultural production. We include here policies targeting prices, agricultural technology, regularization of property rights, credit and risk management instruments, and those directly designed to decrease the environmental damages from agricultural production. For research evaluating policies with multiple goals, we group papers according to their stated primary mechanism.

### Output prices

Prices are a primary lever in determining production choices – in the context of our theory, they shift the level of the agricultural and forest rent functions. While any policy conducted at scale may affect prices, in this section, we focus on output prices. We leave input price subsidies and export price interventions to later sections.

While agricultural price policy has long been at the center of development policy (Timmer 1986), analysis of this approach has often excluded environmental outcomes. A recent global study links spatially-specific crop price indices to global deforestation data, finding that increases in the crop price index explain around 1/3 of the deforestation observed in the tropics between 2001 and 2018, with stronger associations in areas more open to international trade and in less wealthy places (Berman et al. 2023). While this paper highlights a fundamental agriculture/environment tradeoff, crop prices can also change the underlying efficiency of agricultural land use. In Brazil, higher soybean and meat prices and lower wood prices are associated with more deforestation (Hargrave and Kis-Katos 2013; Assunção, Gandour, and Rocha 2015). Further, price decreases can inhibit the profitability of agricultural expansions (Assunção, Gandour, and Rocha 2015).

In addition to price levels, food price stability is strongly associated with food security, political stability, and growth (Amolegbe et al. 2021). Recent work analyzes the impact of maize price volatility and land use change across 26 African countries (Lundberg and Abman 2021), demonstrating that price instability leads to less land conversion. These two papers together highlight the tension that can exist between development and environmental outcomes.

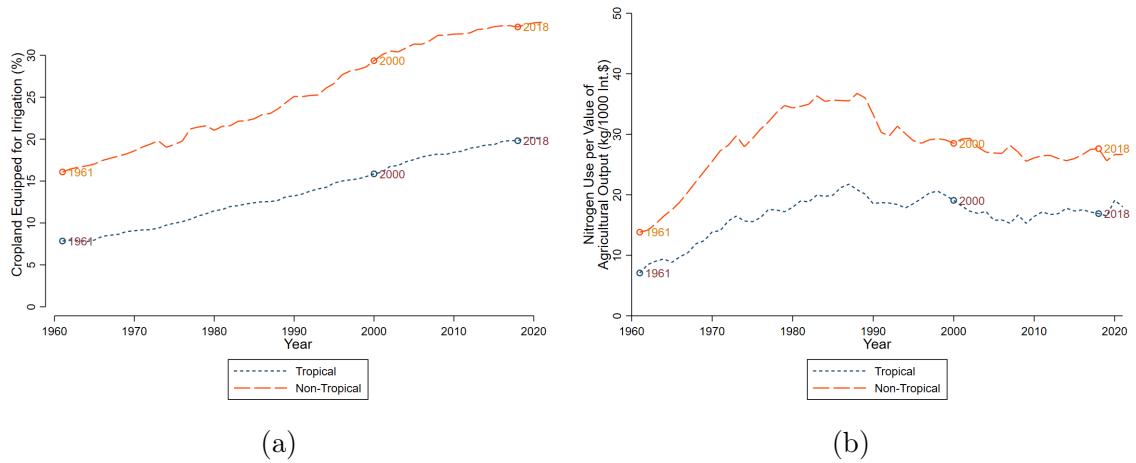
### Technology adoption

Much effort has been expended by governments and international agencies around the promotion of appropriate agricultural technology in the tropics. However, empirical evidence suggests that the same policy to increase intensive agriculture can lead to either increased or decreased preservation. This is consistent with the ambiguous theoretical predictions of the land use effect of increased agricultural productivity. Higher yields or lower production costs

may shift the agricultural rent curve to the right, stimulating land use change, or it may change the tradeoffs between intensive and extensive agriculture, resulting in land sparing.

Figure 5 documents increased input use – irrigation and nitrogen fertilizers, respectively – over time. There is a persistent divergence between tropical and non-tropical countries. Irrigation coverage has increased everywhere over time, with no sign of the gap closing between tropical and non-tropical countries. There does seem to be more convergence in the intensity of fertilizer use, but tropical countries have had a relatively constant rate since the late 1980s. Much of the productivity gap documented in Figure 3 is likely driven by differences in input use.

Figure 5: Evolution of Cropland Equipped for Irrigation and Use of Nitrogen Fertilizer



Note: Cropland equipped for irrigation (as a percentage of total cropland area) over time (a) and the evolution of nitrogen use, measured in kilograms per 1,000 international dollars of agricultural output (b). Final sample: 115 countries (48 non-tropical, 67 tropical) for (a) and 105 countries (44 non-tropical, 61 tropical) for (b).

Three challenges have plagued empirical research in this area. First, technological progress in agriculture has stagnated in poor countries, particularly in Africa. Suri and Udry (2022) argue that this is largely due to multiple binding constraints to technology adoption such as credit constraints, information gaps, and the lack of access to complementary inputs. At the same time, measurable productivity improvements over longer historical periods are set against the lack of credible satellite-based measurements of forest cover before 2000 (Potapov et al. 2022). Second, many agricultural interventions amenable to a randomized design have, thus far, had modest productivity effects (Bridle et al. 2020), making downstream impacts (e.g., deforestation) difficult to precisely estimate. Finally, measurement error in satellite-based detection of forest loss further result in inconclusive or noisy findings (Alix-Garcia and Millimet 2023).

Different methods have yielded different conclusions. For example, Stevenson et al. (2013)

simulate a global economic model using national accounts data to argue that the Green Revolution contributed to 18 to 27 million hectares of avoided deforestation. In an earlier paper, Foster and Rosenzweig (2003) use instrumental variables regression to show that forest growth in India was lower in areas with larger increases in productivity under the Green Revolution. They argue that increases in Indian forest cover were attributable to increased demand for forest products, spurred by technology-induced income and population growth.

Global and regional patterns, however, do suggest that increases in agricultural intensification correspond to reduced deforestation levels (Burney, Davis, and Lobell 2010). More recently, Szerman et al. (2024) use the expansion of farm electrification to study the effects of increases in agricultural productivity on deforestation in Brazil. They demonstrate that electrification increased farm productivity but not the returns to land-extensive cattle production, and find that in the absence of this expansion, deforestation rates in Brazil between 1985 and 2006 would have been 50% larger. A nice feature of this study is that although it relies on historical improvements in productivity, they use satellite imagery to confirm that these effects persisted even twenty-five years after the productivity shock. Focusing on more recent deforestation in Brazil, Carreira, Costa, and Pessoa (2024) find that Brazilian municipalities that adopted high-yield soy varieties deforested less in response to a large increase in export demand from China.

Other work leverages variation in input price policy to study the impact of technology on agricultural deforestation. Abman and Carney (2020) use exogenous variation in subsidies for fertilizers and improved seeds in Malawi to show that these productivity-enhancing investments reduced pressure to expand agriculture and thus reduced deforestation. A recent review describes a suite of pre-2000 papers demonstrating a reduction of deforestation in Zambia with the introduction of price and input subsidies, which was then reversed when the subsidies were removed (Holden 2019). Other evidence from Zambia shows a decrease in deforestation associated with uptake of improved maize seeds, though the opposite correlation exists for fertilizers (Pelletier et al. 2020). Finally, Abman, Garg, et al. (2020) exploit a geographic discontinuity in the targeting of a Ugandan extension program to show that it reduced deforestation by 14%. They are able to detect effects on deforestation, in part, because the program generated a 32% increase in revenue, possibly because it was targeted to low-productivity producers.

Finally, there is intriguing new research on the effects of providing information on the adoption of agricultural water management techniques that can both raise productivity and combat land degradation. In Niger, an experiment with training, conditional, and unconditional cash transfers to encourage the adoption of rainwater collection berms resulted in increases in agricultural production and the restoration of previously uncultivable land (Aker

and Jack 2023). The information intervention alone increased adoption by 90 percentage points, with no additional effect of cash transfers.

The limited set of papers estimating causal effects of agricultural productivity on deforestation means that there remain open questions. A key gap is identifying if there are inflection points when avoided deforestation from intensification is subsumed by increased pressures from extensification.

### Transport and other infrastructure

The improvement of basic infrastructure fundamentally changes the costs of transport and inputs faced by producers. Recalling our framework, transport costs generate the decreasing rent gradients of the Von Thünen model. The rapid expansion of transportation and other infrastructure in the 21st century, coupled with increased availability of granular, spatially-explicit digitized data on these investments, has allowed for recent advances in understanding the causal effects of transport infrastructure on agriculture and deforestation, though few studies examine dual outcomes. Increases in agricultural productivity and food security as a result of better transport infrastructure are documented by Adamopoulos (2025) in Ethiopia and Brenton, Portugal-Perez, and Régolo (2014) in Central and Eastern Africa.

The impact of road investments on forest cover is theoretically ambiguous. New roads may lead to forest loss by facilitating market access for timber, firewood, and agricultural expansion, or by increasing land value for settlements and industries. Conversely, roads might mitigate forest loss by improving access to substitutes for forest resources and enhancing connections to external markets, which could reduce incentives for land clearing. The effects likely differ depending on whether the roads are rural feeder roads or national highways.

Asher, Garg, and Novosad (2020) examine expansions of two different types of road networks in India - last mile rural roads connecting villages that previously only had unpaved roads and highway expansions that serve as major transport arteries. Using a population threshold-based regression discontinuity design, they find that rural roads that led to major reallocation of workers from farm to non-farm employment had zero effect on local forest loss. By contrast, highways dramatically increased deforestation. The result on highways is consistent with previous work in Belize (Chomitz and Gray 2017), Brazil (Pfaff et al. 2018; Bebbington et al. 2018), and Indonesia (Bebbington et al. 2018; Poor et al. 2019). Further, recent evidence suggests that by either ignoring or not fully accounting for general equilibrium effects, the deforestation consequences of highway construction may be underestimated by up to 25% (Araujo, Assunção, and Bragança 2023).

Beyond roads, other work examines specific production infrastructure. Saavedra and Moffette (2025) find that the mass closure of slaughterhouses in Colombia had no effect on

deforestation, nor did they decrease herd sizes or total livestock numbers at the municipality level.

In addition to individual *types* of infrastructure expansions, recent studies examine the effects of programs that encompass many different kinds of infrastructure. Baehr, BenYishay, and Parks (2021) show that irrigation infrastructure reduced forest loss and rural roads did not increase deforestation, suggesting that tailored policies supporting local infrastructure can generate both economic and ecological returns. In Ghana, Abman and Lundberg (2024) study the effect of guaranteed contracts, pricing, and output pickup for palm oil producers. Though the analysis does not provide information on increases in oil palm production, it does detect increased forest loss as a result of its expansion.

### Property rights security

Within a dynamic framework, the risk of future loss of ownership has similar effects to an increase in the discount rate. Such risk incentivizes short-run exploitation of a natural resource. However, theory also demonstrates that this effect may be more complicated when considering a broader portfolio. Liscow (2013) expands earlier work by Farzin (1984) to highlight the mechanisms through which tenure insecurity affects investments across the land portfolio. In particular, landholders with secure tenure may invest more because i) they can use their land as collateral, ii) they feel more secure in making longer-term investments like improving soil quality, or iii) they do not have to waste energy defending their property. Whether this leads to a larger area in agriculture or in forest depends upon the returns to investment in each sector. Within our framework, one way to think about this is that both (expected) rent curves can be shifted outwards by secure property rights, and the final effect on forest is determined by the relative magnitude of these shifts. When the returns to investment in agriculture are higher than those in the forest sector, it may be the case that higher property rights lead to more agriculture at the expense of forests. Liscow (2013) provides evidence of this dynamic in Nicaragua.

Tseng et al. (2021) provide an excellent review of studies published between 1990 and 2018 that examine the relationship between land tenure security, environmental, and human outcomes. Broadly, they find that improvements in property rights improve environmental outcomes and human well-being, including increases in agricultural incomes. They find no cases where an improvement in land tenure security decreased agricultural productivity, and a preponderance of situations in which environmental outcomes improved. This review also highlights the scarcity of studies that examine agricultural and environmental outcomes jointly using rigorous experimental design.

Among the few property rights interventions that examine both agricultural productivity and environmental outcomes is a randomized controlled trial in Benin that delineated the

boundaries of around 70,000 landholdings. Deforestation was significantly lower in villages randomized into the program (Wren-Lewis, Becerra-Valbuena, and Houngbedji 2020). Complementary household survey data indicated that households were less likely to clear land as a means of securing it, more likely to regulate community forest access, and reported higher levels of trust. A separate study of the same program demonstrated higher investment in agriculture but no short term increase in agricultural profits (Goldstein et al. 2018). An RCT in Zambia reveals a different type of effect – increasing land tenure security via demarcation increases recipients' sense of security, but has no impact on long term investments, including in agroforestry (Huntington and Shenoy 2021). Finally, Lipscomb and Prabakaran (2020) use a quasi-experimental approach to examine the rollout of a land registration program in the Amazon. On average, there is no deforestation effect but they do show a decrease in the area under temporary crops. Counties with higher numbers of registrants show decreases in the deforestation rate, consistent with a setting in which agricultural production is used to secure tenure.

In sum, heterogeneous findings likely reflect contextual differences across studies. It would be useful to have more causal evidence characterizing the specific conditions that have led to tenure security improving or worsening agricultural and environmental outcomes.

### **Agri-environmental interventions in the tropics**

In the United States, Canada, and Europe, policies to limit the negative externalities from agriculture while also supporting rural households have become increasingly common (Baylis et al. 2022). These include crop diversification requirements within the European Common Agricultural Policy as well as the US Conservation Reserve Program (CRP), which restores natural vegetation to degraded land. A key question is whether such policies can simultaneously support farmer incomes while conserving environmental services. Much existing evidence is based on case studies or correlational collections of projects (Pretty et al. 2018).

In the tropics, interventions promoting land-sparing agricultural intensification include technological and conservation solutions. In Brazil, an RCT evaluating a large-scale training and technical assistance program found that affected farmers simultaneously increased revenues and carbon sequestration. Farmers were required to learn about one of four sustainable land management practices and a subset were offered visits by field technicians to customize their advice. A key finding was that training alone did not have any impact, but 24 monthly extension visits generated substantial treatment effects on pasture restoration, rotational grazing, improved management and conservation practices, tractor use, and expenditures (Bragança et al. 2022). These results contrast with a payment program intended to encourage sustainable cattle production in Mexico, where cash transfers were allocated to

current livestock producers but not accompanied by training or technical assistance. In this case, there is no evidence that intensification ensued, and municipality-level deforestation increased as a result of the program (Moffette and Alix-García 2024).

Informational interventions have had some successes in increasing the input use efficiency. Such interventions aim to increase or maintain yields while reducing excessive input use linked with environmental externalities. In Nigeria, Arouna et al. (2021) report that an RCT randomizing personalized fertilizer advice via a mobile app increased rice yields and profits without increasing overall fertilizer use. In Bangladesh, implementation of a simple leaf color chart to guide urea application reduced fertilizer use without lowering yields (Islam and Beg 2021).

Agricultural residue burning prior to planting, a common practice across the tropics, generates externalities through carbon emissions (Cassou 2018), cognitive performance (Zivin et al. 2020), and health (Behrer 2019). Recent randomized controlled trials that attempt to refine PES-type contracts for farmers to reduce burning have produced mixed results. A project in Indonesia that offered training, grants for fire fighting, and the promise of a transfer conditional on *no fire* at the end of the growing season generated no detectable effects on fire outcomes (Edwards et al. 2024). An RCT offering up-front versus ex-post payments to reduce burning in India resulted in high takeup from partial upfront payments with no commensurate decrease in agricultural yields. Ex-post payments had no effect on burning. Partial upfront payments reduced the incidence of burning by around 50 percent (Jack et al. 2022).

Agroforestry, an agricultural system integrated with trees, is widely promoted in the tropics. There is significant research on the impacts of agroforestry on outcomes like soil fertility and crop yields, but scant assessment using robust causal methods to measure its effects on both agricultural income and environmental factors. One exception is Hughes et al. (2020), which evaluates an agroforestry extension program in western Kenya. The program trained farmers in agroforestry management and incentivized tree planting with modest payments upon confirmation of tree planting. The evaluation uses a quasi-experimental design to uncover causal impacts after 10 years. Estimated effects included increases in the value of fuelwood and decreases in time spent collecting it, increased use of fodder by dairy farmers as well as higher milk yields. There is a significant evidence gap in this literature. A recent systematic review located only eight quasi-experimental studies of agroforestry interventions and no RCTs (Miller et al. 2020). Only two of these measured environmental outcomes beyond the adoption of the agroforestry practice.

In an attempt to encourage intensification of soy and cattle production in Brazil and simultaneously limit deforestation, industry leaders signed commitments to produce only on

land that had been deforested prior to the agreements. Evidence documents the displacement of soy production in the regulated area onto pastures in that same region, pushing cattle production into an unrelated zone and inducing deforestation (Moffette and Gibbs 2021). Two other articles find that environmental policies can increase agricultural productivity by increasing the implicit cost of deforestation (Koch et al. 2019), perhaps inducing increased uptake of agricultural credit and as such, investment (Moffette, Skidmore, and Gibbs 2021).

In sum, existing work suggests that interventions that convey knowledge, offer continued technical support, and provide financial incentives may increase productivity and preserve ecosystem services. Eliminating one of these elements may compromise success. There remains substantial room for causal evidence on the environmental and agricultural productivity effects of agroforestry, and for studies on PES-type programs that also examine food production outcomes.

### Credit and risk management instruments

Proper access to financial services has long been recognized as a critical factor in the development process, particularly in addressing credit constraints and managing risks (Townsend 1995). Improved credit and risk management increase returns of agricultural investments and can shift the intensive agricultural rent curve upwards. Greater availability of insurance can also decrease the use of forest as an income source of last resort. For farmers deciding between intensive and extensive agricultural practices, the ability to cover upfront costs or bear higher risks can be crucial in enabling sustainable increases in agricultural production. For example, comparing equilibrium models of the US and India, Donovan (2021) suggests that incomplete credit markets decrease agricultural productivity by 16%, primarily by lowering the usage of intermediate inputs (and thus intensive production technologies). In influential work in Ghana, Karlan et al. (2014) demonstrate that uninsured risk is a major barrier to investment, possibly more crucial than improving access to credit in that particular context. Achieving higher food production while preserving ecosystems requires greater capital investments per hectare and the adoption of practices that may involve higher exposure to natural risks.

The evidence on the direct relationship between expanded credit access and deforestation shows mixed results. Exploiting a 2008 policy that conditioned subsidized credit in the Amazon to farmers with legal paperwork and environmental conformity, Assunção, Gandour, Rocha, and Rocha (2020) used a differences-in-differences approach to show that municipalities with less credit reduced deforestation. On the other hand, Assunção, Souza, et al. (2019) use a shift-share approach that combines aggregate fluctuations across banks' funding with local configuration of bank branches serving each municipality in Brazil. Municipalities with better access to credit expanded production through yield gains, reducing the pressure on

deforestation. This result holds largely for areas outside the Amazon, where historical land use has left extensive unproductive cleared areas, creating opportunities to boost agricultural production through productivity gains. In the Amazon, Ruggiero, Pereda, and Pfaff (2025) document heterogeneity in the effects of credit expansion on deforestation. Long-settled areas show no environmental effects of credit expansion, while areas with existing crop production suffered more deforestation as agricultural credit spread, and in more remote areas credit for cattle lead to increases in deforestation.

The evidence directly linking financial market improvements to agricultural and environmental outcomes is weak. However, taken as a whole, this evidence reveals that policies that relax the financial constraints that are pervasive in developing countries should take into account possible threats to forests and other ecosystem services.

## Global context

Most of the evidence that we have reviewed so far focuses on micro-elements of the agricultural production decision. However, these decisions take place within a global context where comparative advantage and trade barriers are primary forces in determining local food prices. The tropics are home to both large amounts of (subsistence) agriculture and critical environmental services through unique tropical biomes. In a Ricardian sense, the tropics have a comparative advantage in tropical forest production and related ecosystem benefits. Thus, to deforest this land for agriculture, agriculture must also possess some comparative advantage in these regions. Puzzlingly, agriculture as a share of employment is high in the tropics, yet agriculture is lower in relative productivity than other sectors in the same countries. According to Lagakos and Waugh (2013), adjusting for prices, the gap in aggregate output per worker between the 90th to 10th percentile of the world's income distribution is 45 to 1 in agriculture, but just 4 to 1 in non-agriculture. Yet agriculture's share of employment averages 65% in 10th percentile countries and only 3% in 90th percentile countries.

Given this evidence, standard Ricardian economic models would suggest that workers should leave agriculture (and thus preserve more forest). Some friction or unobservable thus prevents reallocation in line with economic intuition. The next sections link these macro-level agricultural productivity disparities with environmental outcomes in the tropics.

## Trade

Understanding the link between trade and food production is fundamental to the environmental implications of tropical agriculture. Resource extraction in the tropics can only be efficiently averted insofar as there is cleaner production elsewhere. Brander and Taylor (1995) put forward a fundamental framework linking Ricardian comparative advantage and

resource extraction. The authors emphasize two predictions regarding the effect of trade on environmental degradation. First, if the productivity losses from deforestation are not severe and regulation is quite costly, then open access to forest will ensue. Second, if deforestation would have taken place in the tropics prior to trade liberalization, but the global North is agriculturally more productive than the global South, then liberalization would be good for environmental outcomes.

Recent work by Farrokhi et al. (2024) tests the Brander and Taylor (1995) framework in a modern global computable general equilibrium model. They focus on the effects of liberalizing trade between Brazil and the European Union: a 30% reduction in global agricultural trade costs increases steady-state forest share for world area by 0.8 percentage points. A key insight of their analysis is that when absolute advantage and comparative advantage in agriculture align, then trade liberalization should be deforestation-reducing. However, if absolute advantage in agriculture is misaligned with comparative advantage, trade liberalization will push deforestation across borders to regions of high *comparative* advantage. The authors do not directly calculate the food costs of trade policy-induced deforestation.

Two separate papers calculate how food production is impacted by trade, but do not address deforestation. Tombe (2015) argues that agricultural trade costs tend to be higher in countries with a higher subsistence share of agriculture. Given subsistence agriculture tends to use extensive technologies, this would suggest trade policy is intensifying deforestation. Nath (2025) argues that climate change will only exacerbate this problem unless trade barriers are relaxed. More systematic evidence regarding a joint food-deforestation tradeoff is needed to tie these results and those of Farrokhi et al. (2024) together.

In response to growing discussions regarding trade policy as a deforestation remedy, Harstad (2024) proposes dynamic conservation contracts to protect forest. He argues that static payments for ecosystem services contracts can be expensive and hampered by shifting political priorities, as they require repeatedly paying a targeted country for environmental services while the targeted country has a one-shot deforestation decision at any point. He proposes a conditional trade agreement which provides favorable terms of trade for an extracting country in perpetuity contingent on their keeping resource extraction below some threshold. Theoretically, between two countries, this contract achieves first-best. However, the proposal can be subject to multilateral leakage in more general environments.

Standard trade agreements favoring the production of agricultural goods appear to fail to balance out environmental concerns. Using a panel of 189 countries from 2011 to 2012 and the enactment of regional trade agreements (RTAs) as a quasi-experiment, Abman and Lundberg (2019) find that agricultural land conversion increased by 0.8 percentage points over the three years following the RTAs. Interestingly, this effect is driven by developing tropical countries,

and almost fully by agricultural expansion rather than an increase in forest market expansion. A follow-up study revealed that RTAs with environmental provisions effectively mitigated forest lost from liberalization, seemingly by limiting agricultural extensification (Abman, Lundberg, and Ruta 2024).

While this result suggests that deforestation might be in turn reversed by punitive tariffs, Hsiao (2024) argues that such corrective trade policy needs to be both coordinated and have a dynamic commitment mechanism. In the setting of Indonesian palm oil-driven deforestation, he combines a dynamic model of palm oil supply and a model of oilseed demand with rich cross-oil substitution characteristics to project the deforestation impacts of punitive tariffs. Unilateral trade policy by the EU alone only achieves approximately 20% of the gains of a fully internationally coordinated tariff schedule. These insights connect the empirical evidence from Abman and Lundberg (2019) with an example of dynamic commitment from Harstad (2024).

This global view suggests that price or trade policy can be effective in combating tropical environmental externalities without sacrificing food production. Recent work has shown that distortions in the existing food supply chain can undercut the effectiveness of such policy. For example, Dominguez-Iino (2024) shows that intermediary market power in South America is an important mediator for the effect of soybean prices on deforestation. He argues that taxes on downstream producers (e.g., beef processors) are politically more expedient than taxes on upstream producers (e.g., cattle ranchers), but that these downstream taxes risk leakage due to market power. Market power erodes the Pigouvian signal in a carbon tax, resulting in pass-through rates being cut by more than half in most locations.

### Agricultural price policy

Agricultural price policy is vastly different across the tropics and non-tropical countries. Adamopoulos and Restuccia (2014) measure policy-induced distortions as the (cost-adjusted) difference between farm-gate and international prices. The proposed distortions explain half of the differences in average farm size and agricultural productivity across rich and poor countries. Extensive barriers to large farming in developing countries, such as maximum farm size quotas and progressive taxes on agricultural land, misallocate agricultural resources. New evidence links this potential policy-induced misallocation to explicit environmental outcomes. Carleton, Crews, and Nath (2024) demonstrates that agricultural subsidies have tended to concentrate production in groundwater-depleting regions, like India's Punjab, despite the potential for more efficient cultivation. In a global context, efficient reallocation of agricultural cultivation is hampered by these "distortions to agricultural incentives."

In summary, the global context of tropical food production is a growing field, with research in both macroeconomics and trade as valuable complements to the evidence presented

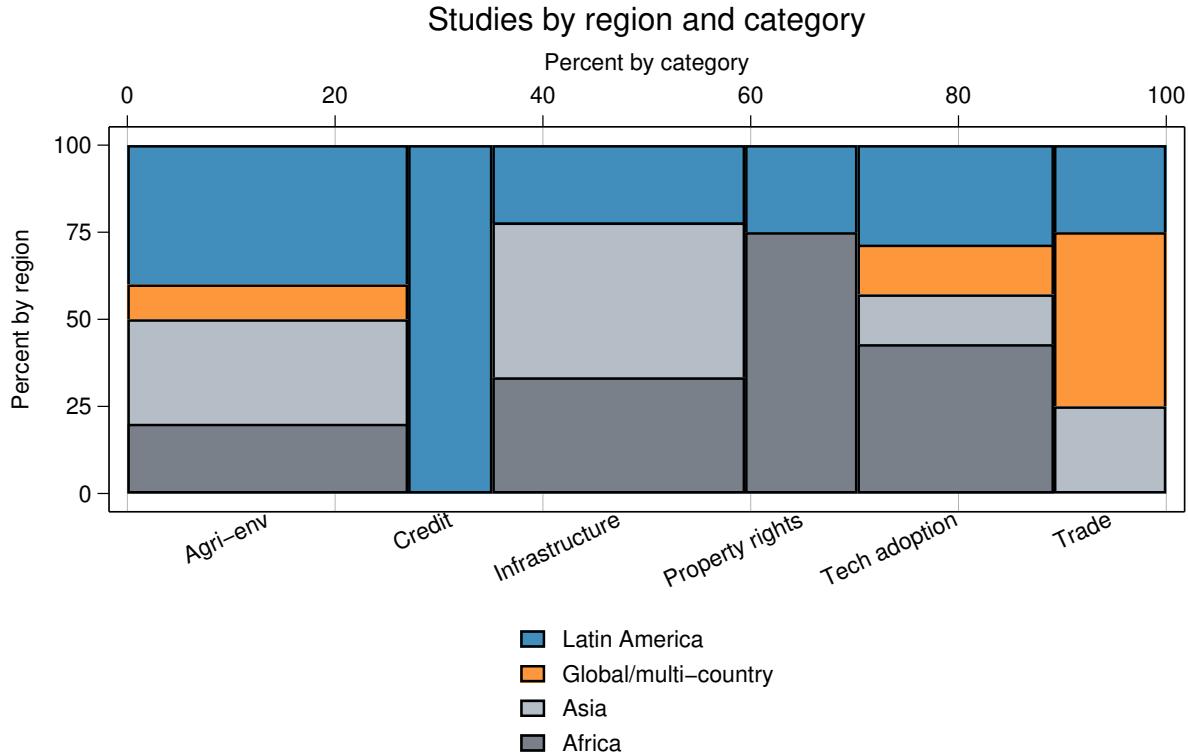
in prior sections. We highlight opportunities to link the micro-econometrically identified phenomena we discuss in prior sections to the large-scale, general equilibrium comparative advantage framework summarized in this section.

## Discussion and future research

The question of how to grow enough food while limiting damage to the ecological system that supports human well-being is foundational to sustainable development. Our review finds very promising work in this area, but also highlights the need for increased investment in research that examines both agricultural and environmental outcomes simultaneously.

When we divide the studies we examine by theme and location, some stylized facts emerge. In general, there is relatively more evidence on technology, agri-environmental interventions, and international trade, although in this last category many of the studies are simulations rather than direct empirical evidence. Latin American countries are well-represented across categories, and there is substantial evidence from African countries on prices, property rights, technology, and infrastructure. Studies taking place in Asia are underrepresented in most categories.

Figure 6: Studies by theme and geographic location



Note: This figure aggregates the studies cited in Table A2 by theme and region. Studies which cover multiple countries across different regions are categorized as global, whereas those that examine countries within the same region are categorized within that region. We exclude review articles from this figure, and only count articles or article pairs that consider both agricultural and environmental outcomes.

Infrastructure improvements, input subsidies, the formalization of property rights, and agricultural extension efforts supporting more sustainable livestock management can yield improvements along both dimensions in some situations. However, it is also clear that the impact of these interventions varies according to context – for example, sustainable livestock management interventions have been successful in improving productivity outcomes without compromising forest cover in Brazil, but not in Mexico. One reason for this seems to be sustained education on the implementation of practices in the former case but not the latter. Similarly, the evidence on road expansion is mixed. This suggests a need to design and study policies within the context of specific countries and their particular market failures, with an emphasis on understanding the specific features that lead to success in a given setting. A deeper analysis of mechanisms may help yield generalizable principles of design that can support win-win policies.

The evidence is weak on technologies to increase agricultural productivity. There is

significant research in this area that we do not review because it does not include proxies for environmental outcomes. This omission is in itself revealing. Beyond disciplinary disconnects, some of this is due to the nature of RCTs. These tend to be relatively small scale, with small impacts. They often do not contain spatially explicit information on plot location. These features, combined with the fact that many environmental effects are longer-term, have spatial spillovers, and require large samples to detect impacts, means that it is difficult to produce work that examines the environmental effects of agricultural productivity increases. It is crucial to expand this body of work by incentivizing localized measurement of environmental outcomes.

Agri-environmental policies are a promising avenue for joint success in tropical countries. The evidence suggests that careful design, including a combination of technical assistance and financial incentives, may be fruitful. Informational interventions have demonstrated positive yield and environmental effects associated with more efficient fertilizer use. However, there is ample room for further evidence, both geographically and in terms of design elements.

Efforts to achieve the twin goals of food and environmental quality cannot escape their broader context. Global analyses highlight the role of distortions in getting food to where it is most needed, and predict that the tropics should not use as much land for agriculture as they currently do. Theory highlights an important role for trade policy, although empirical evidence suggests that liberalizing agricultural trade requires coordinated and targeted policy to successfully avoid adverse environmental impacts. There is substantial room for evidence on how technology and market power shift food production across space – we know that both of these elements have created distortions, and the question of how to design policy to reduce these remains. Finally, global evaluations of misallocation in agriculture have developed rich insights regarding the role of land and agricultural subsidies, but the environmental impact of these large-scale policies in full, global general equilibrium is still an open question. As indicated by the micro-evidence, targeting these existing policy levers effectively can generate win-win policies for agricultural yields and environmental outcomes, but more evidence is needed on how to scale such interventions.

## References

- Abman, R. and C. Carney (2020). “Agricultural productivity and deforestation: Evidence from input subsidies and ethnic favoritism in Malawi”. *Journal of Environmental Economics and Management* 103, p. 102342.
- Abman, R., T. Garg, Y. Pan, and S. Singhal (2020). “Agriculture and Deforestation”. *SSRN*. URL: <https://ssrn.com/abstract=3692682>.
- Abman, R. and C. Lundberg (2019). “Does Free Trade Increase Deforestation? The Effects of Regional Trade Agreements”. *Journal of the Association of Environmental and Resource Economists* 7 (1), pp. 35–72.
- (2024). “Contracting, market access and deforestation”. *Journal of Development Economics* 168.
- Abman, R., C. Lundberg, and M. Ruta (2024). “The effectiveness of environmental provisions in regional trade agreements”. *Journal of the European Economic Association* 22.6, pp. 2507–2548.
- Adamopoulos, T. (2025). “Spatial integration and agricultural productivity: Quantifying the impact of new roads”. *American Economic Journal: Macroeconomics* 17.1, pp. 343–378.
- Adamopoulos, T. and D. Restuccia (2014). “The Size Distribution of Farms and International Productivity Differences”. *American Economic Review* 104 (6), pp. 1667–1697.
- Aker, J. C. and B. K. Jack (2023). “Harvesting the rain: The adoption of environmental technologies in the Sahel”. *Review of Economics and Statistics*, pp. 1–52.
- Alix-Garcia, J. and D. L. Millimet (2023). “Remotely incorrect? Accounting for nonclassical measurement error in satellite data on deforestation”. *Journal of the Association of Environmental and Resource Economists* 10.5, pp. 1335–1367.
- Amolegbe, K. B., J. Upton, E. Bageant, and S. Blom (2021). “Food price volatility and household food security: Evidence from Nigeria”. *Food Policy* 102.
- Angelsen, A. (2007). *Forest cover change in space and time: combining the von Thünen and forest transition theories*. Vol. 4117. World Bank Publications.
- (2010). “Policies for reduced deforestation and their impact on agricultural production.” *Proceedings of the National Academy of Sciences of the United States of America* 107 (46), pp. 19639–19644.
- Araujo, R., J. Assunção, and A. A. Bragaña (2023). “The Effects of Transportation Infrastructure on Deforestation in the Amazon”. *World Bank Policy Research Working Paper* 10415.
- Arouna, A., J. D. Michler, W. G. Yergo, and K. Saito (2021). “One size fits all? Experimental evidence on the digital delivery of personalized extension advice in Nigeria”. *American Journal of Agricultural Economics* 103.2, pp. 596–619.
- Asher, S., T. Garg, and P. Novosad (2020). “The ecological impact of transportation infrastructure”. *Economic Journal* 130 (629), pp. 1173–1199.
- Assunção, J., C. Gandour, R. Rocha, and R. Rocha (2020). “The effect of rural credit on deforestation: Evidence from the Brazilian Amazon”. *The Economic Journal* 130.626, pp. 290–330.
- Assunção, J., C. Gandour, and R. Rocha (2015). “Deforestation slowdown in the Brazilian Amazon: prices or policies?” *Environment and Development Economics*, pp. 1–5.

- Assunção, J., P. Souza, P. Fernandes, and S. Mikio (2019). “Does credit boost agriculture? Impacts on Brazilian rural economy and deforestation”. In: *LACEA-LAMES Annual Meeting*. Vol. 24.
- Baehr, C., A. BenYishay, and B. Parks (2021). “Linking Local Infrastructure Development and Deforestation: Evidence from Satellite and Administrative Data”. *Journal of the Association of Environmental and Resource Economists* 8 (2), pp. 375–409.
- Balboni, C., A. Berman, R. Burgess, and B. A. Olken (2023). “The Economics of Tropical Deforestation”. *Annual Review of Economics*.
- Barbier, E. B. (2004). “Explaining agricultural land expansion and deforestation in developing countries”. *American Journal of Agricultural Economics* 86.5, pp. 1347–1353.
- Barbier, E. B. (2001). “The Economics of Tropical Deforestation and Land Use: An Introduction to the Special Issue”. *Land Economics* 77 (2), pp. 155–171.
- Baylis, K., J. Coppess, B. M. Gramig, and P. Sachdeva (2022). “Agri-environmental Programs in the United States and Canada”. *Review of Environmental Economics and Policy* 16 (1), pp. 83–104.
- Bebbington, A. J., D. Humphreys Bebbington, L. A. Sauls, J. Rogan, S. Agrawal, C. Gamboa, A. Imhof, K. Johnson, H. Rosa, A. Royo, T. Toumbourou, and R. Verдум (2018). “Resource extraction and infrastructure threaten forest cover and community rights”. *Proceedings of the National Academy of Sciences* 115.52, pp. 13164–13173.
- Behrer, A. P. (2019). “Earth, Wind and Fire: The impact of anti-poverty efforts on Indian agriculture and air pollution”. *Working Paper*.
- Berman, N., M. Couttenier, A. Leblois, and R. Soubeyran (2023). “Crop prices and deforestation in the tropics”. *Journal of Environmental Economics and Management* 119.
- Bragança, A., P. Newton, A. Cohn, J. Assuncao, C. Camboim, D. D. Faveri, B. Farinelli, V. M. E. Perego, M. Tavares, J. Resende, S. D. Medeiros, and T. D. Searchinger (2022). “Extension services can promote pasture restoration: Evidence from Brazil’s low carbon agriculture plan”. *Proceedings of the National Academy of Sciences* 119 (12).
- Brander, J. A. and M. S. Taylor (1995). “International Trade and Open Access Renewable Resources: The Small Open Economy Case”. *National Bureau of Economic Research Working Paper Series* No. 5021. URL: <http://www.nber.org/papers/w5021%20http://www.nber.org/papers/w5021.pdf>.
- Brenton, P., A. Portugal-Perez, and J. Régolo (2014). “Food prices, road infrastructure, and market integration in Central and Eastern Africa”. *World Bank Policy Research Working Paper* 7003.
- Bridle, L., J. Magruder, C. McIntosh, and T. Suri (2020). “Experimental insights on the constraints to agricultural technology adoption”. *UC Berkeley CEGA White Papers*.
- Burney, J. A., S. J. Davis, and D. B. Lobell (2010). “Greenhouse gas mitigation by agricultural intensification”. *Proceedings of the national Academy of Sciences* 107.26, pp. 12052–12057.
- Busch, J. and K. Ferretti-Gallon (2017). “What drives deforestation and what stops it? A meta-analysis”. *Review of Environmental Economics and Policy* 11 (1), pp. 3–23.
- (2023). “What drives and stops deforestation, reforestation, and forest degradation? An updated meta-analysis”. *Review of Environmental Economics and Policy* 17.2, pp. 217–250.

- Carleton, T., N. L. Crews, and I. Nath (2024). "Agriculture, Trade, and the Spatial Efficiency of Global Water Use". *Manuscript, UC Berkeley*.
- Carreira, I., F. Costa, and J. P. Pessoa (2024). "The deforestation effects of trade and agricultural productivity in Brazil". *Journal of Development Economics* 167, p. 103217.
- Cassou, E. (2018). "Agricultural Pollution: Field Burning". *Note: World Bank Group*. URL: <https://documents.worldbank.org/en/publication/documents-reports/documentdetail/989351521207797690/field-burning>.
- Chomitz, K. M. and D. A. Gray (2017). "Roads, land use, and deforestation: A spatial model applied to Belize". In: *The Economics of Land Use*. Routledge, pp. 289–314.
- Dominguez-Iino, T. (2024). "Efficiency and Redistribution in Environmental Policy: An Equilibrium Analysis of Agricultural Supply Chains". URL: [https://tdomingueziino.github.io/tomas\\_domingueziino\\_jmp.pdf](https://tdomingueziino.github.io/tomas_domingueziino_jmp.pdf).
- Donovan, K. (2021). "The Equilibrium Impact of Agricultural Risk on Intermediate Inputs and Aggregate Productivity". *The Review of Economic Studies* 88 (5), pp. 2275–2307.
- Edwards, R., W. Falcon, G. Hadiwidjaja, M. Higgins, R. Naylor, and S. Sumarto (2024). "Fight fire with finance: A randomized field experiment to curtail land-clearing fire in Indonesia". *Revise and Resubmit at the Journal of Political Economy Microeconomics*.
- FAOStat (2024). FAOSTAT: Land Use. [Accessed on 16 October 2024]. URL: <https://www.fao.org/faostat/en/#data/RL>.
- Farrokhi, F., E. Kang, H. Pellegrina, and S. Sotelo (2024). "Deforestation: A Global and Dynamic Perspective". URL: [https://public.websites.umich.edu/~ssotelo/research/FKPS\\_deforestationGE.pdf](https://public.websites.umich.edu/~ssotelo/research/FKPS_deforestationGE.pdf).
- Farzin, Y. H. (1984). "The Effect of the Discount Rate on Depletion of Exhaustible Resources". *Journal of Political Economy* 92 (5).
- Foster, D. and R. Rosenzweig (2003). "Economic Growth and the Rise of Forests". *The Quarterly Journal of Economics* 118 (2), pp. 601–637.
- García, A. (2020). "The Environmental Impacts of Agricultural Intensification". *CGIAR Standing Panel on Impact Assessment Technical Note* (9). URL: [https://cgspage.cgiar.org/handle/10568/108993%0Ahttps://cgspage.cgiar.org/bitstream/handle/10568/108993/Environmental%20Impacts%20of%20Ag%20Intensification%20TN9\\_July2020.pdf?sequence=2&isAllowed=y](https://cgspage.cgiar.org/handle/10568/108993%0Ahttps://cgspage.cgiar.org/bitstream/handle/10568/108993/Environmental%20Impacts%20of%20Ag%20Intensification%20TN9_July2020.pdf?sequence=2&isAllowed=y).
- Global Forest Watch (2024). *Global Deforestation Rates & Statistics by Country*. [Accessed in November 2024]. URL: <https://www.globalforestwatch.org/dashboards/global/>.
- Goldstein, M., K. Houngbedji, F. Kondylis, M. O'Sullivan, and H. Selod (2018). "Formalization without certification? Experimental evidence on property rights and investment". *Journal of Development Economics* 132, pp. 57–74.
- Greenhalgh, T., S. Thorne, and K. Malterud (2018). "Time to challenge the spurious hierarchy of systematic over narrative reviews?" *European journal of clinical investigation* 48.6.
- Hargrave, J. and K. Kis-Katos (2013). "Economic causes of deforestation in the Brazilian Amazon: a panel data analysis for the 2000s". *Environmental and Resource Economics* 54, pp. 471–494.
- Harstad, B. (2024). "Trade and Trees". *American Economic Review: Insights* 6 (2), pp. 155–175.

- Holden, S. T. (2019). "Economics of Farm Input Subsidies in Africa". *Annual Review of Resource Economics* 11, pp. 501–522.
- Hsiao, A. (2024). "Coordination and Commitment in International Climate Action: Evidence from Palm Oil".
- Hughes, K., S. Morgan, K. Baylis, J. Oduol, E. Smith-Dumont, T. G. Vågen, and H. Kegode (2020). "Assessing the downstream socioeconomic impacts of agroforestry in Kenya". *World Development* 128.
- Huntington, H. and A. Shenoy (2021). "Does insecure land tenure deter investment? Evidence from a randomized controlled trial". *Journal of Development Economics* 150, p. 102632.
- Islam, M. and S. Beg (2021). "Rule-of-Thumb Instructions to Improve Fertilizer Management: Experimental Evidence from Bangladesh". *Economic Development and Cultural Change* 70.1, pp. 237–281.
- Jack, B. K., S. Jayachandran, N. Kala, and R. Pande (2022). "Money (Not) to Burn: Payments for Ecosystem Services to Reduce Crop Residue Burning". *NBER Working Paper Series* (30690). URL: <https://www.nber.org/papers/w30690>.
- Jayachandran, S. (2022). "How Economic Development Influences the Environment". *Annual Review of Economics* 14 (August).
- Jayathilake, H. M., G. W. Prescott, L. R. Carrasco, M. Rao, and W. S. Symes (2021). "Drivers of deforestation and degradation for 28 tropical conservation landscapes". *Ambio* 50.1, pp. 215–228.
- Karlan, D., R. Osei, I. Osei-Akoto, and C. Udry (2014). "Agricultural decisions after relaxing credit and risk constraints". *The Quarterly Journal of Economics* 129.2, pp. 597–652.
- Koch, N., E. zu Ermgassen, J. Wehkamp, F. O. Filho, and G. Schwerhoff (2019). "Agricultural Productivity and Forest Conservation: Evidence from the Brazilian Amazon". *American Journal of Agricultural Economics*, pp. 1–22.
- Lagakos, D. and M. E. Waugh (2013). "Selection, Agriculture, and Cross-Country Productivity Differences". *American Economic Review* 103 (2), pp. 948–980.
- Lipscomb, M. and N. Prabakaran (2020). "Property rights and deforestation: Evidence from the Terra Legal land reform in the Brazilian Amazon". *World Development* 129, p. 104854.
- Liscow, Z. D. (2013). "Do property rights promote investment but cause deforestation? Quasi-experimental evidence from Nicaragua". *Journal of Environmental Economics and Management* 65 (2), pp. 241–261.
- Lundberg, C. and R. Abman (2021). "Maize price volatility and deforestation". *American Journal of Agricultural Economics*, pp. 1–24.
- Miller, D. C., P. J. Ordoñez, S. E. Brown, S. Forrest, N. J. Nava, K. Hughes, and K. Baylis (2020). "The impacts of agroforestry on agricultural productivity, ecosystem services, and human well-being in low-and middle-income countries: An evidence and gap map". *Campbell Systematic Reviews* 16 (1).
- Moffette, F. and J. Alix-García (2024). "Agricultural subsidies: cutting into forest conservation?" *Environment and Development Economics*.
- Moffette, F. and H. K. Gibbs (2021). "Agricultural Displacement and Deforestation Leakage in the Brazilian Legal Amazon". *Land Economics* 101 (2), pp. 155–179.
- Moffette, F., M. Skidmore, and H. K. Gibbs (2021). "Environmental policies that shape productivity: Evidence from cattle ranching in the Amazon". *Journal of Environmental Economics and Management* 109, p. 102490.

- Nath, I. B. (2025). "Climate Change, The Food Problem, and the Challenge of Adaptation through Sectoral Reallocation". *Journal of Political Economy* 133.6.
- Pelletier, J., H. Ngoma, N. M. Mason, and C. B. Barrett (2020). "Does smallholder maize intensification reduce deforestation? Evidence from Zambia". *Global Environmental Change* 63, p. 102127.
- Pfaff, A., J. Robalino, E. J. Reis, R. Walker, S. Perz, W. Laurance, C. Bohrer, S. Aldrich, E. Arima, M. Caldas, et al. (2018). "Roads & SDGs, tradeoffs and synergies: learning from Brazil's Amazon in distinguishing frontiers". *Economics* 12.1, p. 20180011.
- Phalan, B., R. E. Green, L. V. Dicks, G. Dotta, C. Feniuk, A. Lamb, B. B. Strassburg, D. R. Williams, E. K. Zu Ermgassen, and A. Balmford (2016). "How can higher-yield farming help to spare nature?" *Science* 351.6272, pp. 450–451.
- Pichon, F. J. (1997). "Colonist Land-Allocation Decisions, Land Use, and Deforestation in the Ecuadorian Amazon Frontier". *Economic Development and Cultural Change* 45.4, pp. 707–744.
- Poor, E. E., V. I. Jati, M. A. Imron, and M. J. Kelly (2019). "The road to deforestation: Edge effects in an endemic ecosystem in Sumatra, Indonesia". *PLoS One* 14.7, e0217540.
- Potapov, P., M. C. Hansen, A. Pickens, A. Hernandez-Serna, A. Tyukavina, S. Turubanova, V. Zalles, X. Li, A. Khan, F. Stolle, N. Harris, X.-P. Song, A. Baggett, I. Kommareddy, and A. Kommareddy (2022). "The Global 2000-2020 Land Cover and Land Use Change Dataset Derived From the Landsat Archive: First Results". *Frontiers in Remote Sensing* 3.
- Pretty, J., T. G. Benton, Z. P. Bharucha, L. V. Dicks, C. B. Flora, H. C. J. Godfray, D. Goulson, S. Hartley, N. Lampkin, C. Morris, et al. (2018). "Global assessment of agricultural system redesign for sustainable intensification". *Nature Sustainability* 1.8, pp. 441–446.
- Ruggiero, P., P. Pereda, and A. Pfaff (2025). "When does rural credit drive Amazon Deforestation?" *Manuscript*. URL: <https://ssrn.com/abstract=5011215>.
- Saavedra, S. and F. Moffette (2025). "Deforestation, Market Linkages, and Health: Evidence from Slaughterhouse Closures in Colombia". *Working Paper Available at SSRN*: <https://ssrn.com/abstract=5289649>.
- Stevenson, J. R., N. Villoria, D. Byerlee, T. Kelley, and M. Maredia (2013). "Green Revolution research saved an estimated 18 to 27 million hectares from being brought into agricultural production". *Proceedings of the National Academy of Sciences* 110 (21), pp. 8363–8368.
- Suri, T. and C. Udry (2022). "Agricultural technology in Africa". *Journal of Economic Perspectives* 36.1, pp. 33–56.
- Szerman, D., J. J. Assunção, M. Lipscomb, and A. M. Mobarak (2024). "Agricultural productivity and deforestation: Evidence from Brazil". *Journal of the Association of Environmental and Resource Economists*.
- Timmer, C. P. (1986). *Getting prices right: The scope and limits of agricultural price policy*. Cornell University Press.
- Tombe, T. (2015). "The Missing Food Problem: Trade, Agriculture, and International Productivity Differences". *American Economic Journal: Macroeconomics* 7 (3), pp. 226–258.
- Townsend, R. (1995). "Consumption insurance: An evaluation of risk-bearing systems in low-income economies". *The Journal of Economic Perspectives* 9.3, pp. 83–102.

- Tseng, T. W. J. et al. (2021). "Influence of land tenure interventions on human well-being and environmental outcomes". *Nature Sustainability* 4 (3), pp. 242–251.
- Tyukavina, A., A. Baccini, M. C. Hansen, P. V. Potapov, S. V. Stehman, R. A. Houghton, A. M. Krylov, S. Turubanova, and S. J. Goetz (2015). "Aboveground carbon loss in natural and managed tropical forests from 2000 to 2012". *Environmental Research Letters* 10 (7).
- UN (2022). *World Population Prospects 2022 Summary of Results*. Department of Economic and Social Affairs, Population Division, United Nations. URL: [https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/wpp2022\\_summary\\_of\\_results.pdf](https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/wpp2022_summary_of_results.pdf).
- Villoria, N. B., D. Byerlee, and J. Stevenson (2014). "The effects of agricultural technological progress on deforestation: What do we really know?" *Applied Economic Perspectives and Policy* 36 (2), pp. 211–237.
- World Population Review (2024). *Tropical Countries 2024*. Accessed in November 2024. URL: <https://worldpopulationreview.com/country-rankings/tropical-countries>.
- Wren-Lewis, L., L. Becerra-Valbuena, and K. Houngbedji (2020). "Formalizing land rights can reduce forest loss: Experimental evidence from Benin". *Science Advances* 6 (26).
- Zivin, J. G., T. Liu, Y. Song, Q. Tang, and P. Zhang (2020). "The unintended impacts of agricultural fires: Human capital in China". *Journal of Development Economics* 147, p. 102560.

# Supplemental Material

## Tradeoffs and synergies for agriculture and environmental outcomes in the tropics

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### A Tropical and Non-Tropical Countries

Table A1: Classification of World Countries as Tropical and Non-Tropical

Tropical Countries (106)	Non-Tropical Countries (92)
American Samoa	Angola
Anguilla	Antigua and Barbuda
Bahamas	Bangladesh
Barbados	Belize
Benin	Bermuda
Bolivia	Botswana
Brazil	British Virgin Islands
Burkina Faso	Cambodia
Cameroon	Cape Verde
Cayman Islands	Central African Republic
China	Colombia
Cook Islands	Costa Rica
Côte d'Ivoire	Cuba
Cyprus	Dominican Republic
Dominica	D.R. of the Congo
El Salvador	Ecuador
Eritrea	Equatorial Guinea
Fiji	Ethiopia
Gabon	French Polynesia
Ghana	Gambia
Guadeloupe	Grenada
Guatemala	Guam
Guinea	Guinea-Bissau
Guyana	Honduras
India	Indonesia
Jamaica	Kiribati
Laos	Liberia
Madagascar	Malawi
Malaysia	Marshall Islands
Martinique	Mauritius
Mayotte	Mexico
Micronesia	Mozambique
Myanmar	Nepal
Nicaragua	Niue
Northern Mariana Islands	Palau
Panama	Papua New Guinea
Paraguay	Peru
Philippines	Pitcairn
Puerto Rico	Réunion
Rwanda	Saint Kitts and Nevis
Saint Lucia	Saint Martin
St. Vincent and Grenadines	Samoa
Sao Tome and Principe	Senegal
Seychelles	Sierra Leone
Solomon Islands	Somalia
Sri Lanka	Sudan
Suriname	Thailand
Tonga	Trinidad and Tobago
Turks and Caicos Islands	Tuvalu
Uganda	Tanzania
Vanuatu	Venezuela
Vietnam	Wallis and Futuna Islands
Zambia	Zimbabwe
	Afghanistan
	Algeria
	Argentina
	Australia
	Belarus
	Bhutan
	Brunei Darussalam
	Canada
	Croatia
	Denmark
	Estonia
	Faroe Islands
	France
	Germany
	Greece
	Guernsey
	Iceland
	Iraq
	Isle of Man
	Italy
	Jersey
	Kazakhstan
	Kyrgyzstan
	Lebanon
	Libya
	Lithuania
	Macedonia
	Monaco
	Montenegro
	Morocco
	New Caledonia
	Norfolk Island
	Pakistan
	Portugal
	Romania
	San Marino
	Slovakia
	South Korea
	Swaziland
	Switzerland
	Tajikistan
	Turkey
	Ukraine
	United States of America
	Uzbekistan

Note: This table comprises 106 tropical countries and 92 non-tropical countries, as classified by the authors based on the World Population Review's classification system (World Population Review 2024). The World Population Review defines tropical countries as those located in the belt-shaped region closest to the Equator, bordered by the Tropic of Cancer to the north and the Tropic of Capricorn to the south. This classification includes nations such as the United States and Argentina, which are not typically recognized as tropical due to their limited areas within tropical boundaries. The authors do not classify these countries as tropical to avoid skewing the results. Tropical countries with less than 10% of tree cover in 2000 were excluded from the sample. To maintain stability in data reporting before and after the Cold War, Russia was also removed from the analysis.

Table A2: Recent papers providing evidence on agriculture and the environment

Category	Authors	Intervention	Country	Agriculture effect	Environmental effect
Agri-environmental interventions	Arouna, A., Michler, J. D., Yergo, W. G., & Saito, K. (2021)	Mobile app with fertilizer recommendations	Nigeria	Positive effect on rice yields and on profits	Fertilizer use remained the same (neutral effect on environment)
Agri-environmental interventions	Bragança, A. Newton, P., Cohn, A., Assunção, J., Camboim, C., De Faveri, D., Farinelli, B., Perego, V., Tavares, M., Resende, J., De Medeiros, S., Searchinger, T. (2022)	Extension services to promote pasture restoration practices	Brazil	Increased productivity of pasture	Decreased greenhouse gas emissions
Agri-environmental interventions	Edwards, R., Hadiwidjaja, G., Naylor, R. (2022)	Training, up-front payment for investment in fire suppression, ex post payment for not burning agricultural fields	Indonesia	Not directly measured, but no change in land use outcome	No effect on environment

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Category	Authors	Intervention	Country	Agriculture effect	Environmental effect
Agri-environmental interventions	Hughes et al. (2020)	Technical assistance for agroforestry with tree seeds distributed for free, small incentive upon confirmation of planted trees	Kenya	Increases in fuelwood sales, milk production, use of fodder	Increase in number and diversity of trees planted within agricultural plots
Agri-environmental interventions	Islam, M., & Beg, S. (2021)	Chart and training to help identify nitrogen deficiency in rice	Bangladesh	Yields remained the same	Fertilizer use increased
Agri-environmental interventions	Jack, B. K., Jayachandran, N. Kala, and R. Pande (2022)	Payments to India not burn agricultural fields; comparison of partially upfront versus fully conditional payments	India	No detected treatment effect on agricultural yields	Upfront increased burning; no effect of ex-post only PES
Agri-environmental interventions	Koch, N. Zu Ermagasse, E., Wehkamp, J., Oliveira, F. (2019)	Feld inspections and fines for deforestation (Municípios Prioritários)	Brazil	No effect on dairy or crop production	Reduced deforestation

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Category	Authors	Intervention	Country	Agriculture effect	Environmental effect
Agri-environmental interventions	Miller, D., P. J. Ordoñez, S. E. Brown, S. Forrest, N. J. Nava, K. Hughes, and K. Baylis (2020)	Agroforestry	Malawi, Kenya, Nicaragua, Zambia, Colombia, Indonesia, Mozambique	Review paper: no summary of effects offered	Review paper: no summary of effects offered
Agri-environmental interventions	Moffette, F., H. Gibbs, (2021)	Producer agreements (soy moratorium; zero deforestation cattle agreement)	Brazil	The soy moratorium and zero deforestation cattle agreements in the Amazon increased soy and cattle production in the neighboring, unregulated Cerrado Biome.	Deforestation increased in Cerrado Biome
Credit	Moffette, F., G4 Agreement, Priority List H. (2021)	Cattle	Brazil	Productivity of cattle production increased	Reduced deforestation inferred from other papers
	Assunção, J., Gândour, C., Rocha, R., & Rocha, R. (2020).	Rural credit	Brazil	Not directly assessed	Reduction in deforested area

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Category	Authors	Intervention	Country	Agriculture effect	Environmental effect
Credit	Assunção, J., Souza, P., Fernandes, P., & Mikio, S. (2019)	Rural credit	Brazil	Positive effect on crop production and land productivity	Reduction in pasture area, increase in forested areas
Credit	Ruggiero, P., Pereda, P., & Pfaff, A. (2024)	Rural Credit	Brazil	Not measured	Conditional on baseline use – ag credit increases deforestation in areas with high baseline ag, pasture credit in areas with high baseline pasture
Global	Abman, R., Lundberg, C. (2019)	Regional Agreements (RTA), trade liberalization	189 countries	Increased agricultural output	Increased conversion of forest to ag
Global	Abman, R., Lundberg, C., & Ruta, M. (2024)	RTAs	Global	Decreased ag area and trade	Decreased deforestation
Global	Dominguez-Iino (2023)	Carbon tax on farmers, downstream business taxes	South America	Decreases	Decreases

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Category	Authors	Intervention	Country	Agriculture effect	Environmental effect
Global	Hsiao (2024)	Import tariffs on palm oil	Indonesia and Malaysia	Decreases	Decreases
Infrastructure	Abman, R. and Lundberg, C. (2024)	Guaranteed contracts and on-farm pick up	Ghana	Not directly measured – increase in household benefits inferred from other evidence	Increased deforestation
Infrastructure	Adamopoulos (2025)	Road expansion	Ethiopia	Increased agricultural productivity	Not directly assessed
Infrastructure	Araujo et al. (2023)	Road expansion	Brazil	Not directly assessed	Increased deforestation due to improved market access and altered land use decisions
Infrastructure	Asher, S., T. Garg, and P. Novosad (2020)	Construction of new rural roads and highways	India	Did not study effect on food production.	Rural roads had precise zero effect.
Infrastructure	Baehr, C., A. BenYishay, and B. Parks (2021)	Irrigation and rural road investment	Cambodia	Asher and Novosad (2020) studied effect of rural roads on labor in agriculture. Rural roads reduced labor in agriculture by 10 percentage points or 20%.	Highway upgrades increased forest loss.
Infrastructure				Intensification of production on already cleared lands	Either no effect or reduced deforestation

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Category	Authors	Intervention	Country	Agriculture effect	Environmental effect
Infrastructure	Brenton et al. (2014)	Road infrastructure development	Central and Eastern Africa	Not directly assessed; greater market integration as measured by relative prices.	Not directly assessed
Infrastructure	Garg, Jagannani and Pullabhotla (2024)	Road Expansion	India	Did not study effect on food production. Asher and Novosad (2020) studied effect of rural roads on labor in agriculture. Rural roads reduced labor in agriculture by 10 percentage points or 20%.	Increased crop fires
Infrastructure	Poor et al. (2019)	Road expansion	Indonesia	Not directly assessed	Negative. Increased deforestation and forest fragmentation due to road expansion.
Infrastructure	Saavedra, S., Moffette, F. (2025)	Slaughterhouse closure	Colombia	No effect on cattle herd and productivity	No effect on deforestation
Prices	Abman, R., Carney, C. (2020)	Fertilizer and seed subsidy	Malawi	Increased agricultural productivity	Reduced deforestation
Prices	Assuncao, J., Gandour, C., Rocha, R. (2015)	Output prices and conservation policies	Brazil	2004 conservation policies increase GDP per capita, decreased sowed area in agriculture. 2008 policies increased cattle herds	Output prices increase deforestation while conservation policies decreased it

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Category	Authors	Intervention	Country	Agriculture effect	Environmental effect
Prices	Berman (2023)	Increase in output prices	Global	Not directly measured – infer from other literature that higher prices induce more agricultural production	Increase in deforestation
Prices	Hargrave, J. and Katos, K. (2013)	Output prices, fines, protected areas	Brazil	Not analyzed	Reduced deforestation
Prices	Lundberg, C. and Abman, R. (2021)	Volatility in local maize prices	26 Sub-Saharan African countries	Not empirically measured: theoretical model and previous literature suggest that higher price volatility decreases incentives for investment in agriculture	Decreased deforestation
Property rights	Goldstein, Kondylis, O'Sullivan, Selod (2018)	Mapping of agricultural land	Benin	Indirect, but detected increase in long term investments related to productivity.	Increased tree planting; also see companion paper Wren-Lewis et al (2020)
Property rights	Huntington, H. and A. Shenoy (2021)	Field demarcation and certification; agroforestry extension	Zambia	No impacts on fallowing of cropland, fertilizer usage, or uptake of labor	Presence of agroforestry increases in households receiving extension, but has no interaction with tenure

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Category	Authors	Intervention	Country	Agriculture effect	Environmental effect
Property rights	Lipscomb, M., Prabakaran, N. (2020)	Land tenure registration (Terra Legal)	Brazil	Decrease in temporary crop area	No average effect, but significant decrease in deforestation in countries with more regularization
Property rights	Wren-Lewis, L., Becerra-Valbuena, and Houngbedji (2020)	Mapping of agricultural land	Benin	See companion paper Goldstein et al (2018)	Reduction in deforestation in treated villages
Technology Adoption	Assunção, J., A.M. Mobarak, and D. Szerman (2024)	Electrification via hydro power	Brazil	Higher yields	Lower deforestation
Technology Adoption	Abman Garg, Pan, Singh, R., T., Y., S. (2020)	Extension, crop rotation	Uganda	Adoption of sustainable agricultural practices increased revenues.	Reduction in deforestation
Technology Adoption	Aker, J. and B.K. Jack (2023)	Information, unconditional and conditional cash transfers to encourage use of demi-lunes for water conservation	Niger	Higher agricultural output	Restoration of previously uncultivable land, subjective improvements in soil quality

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Category	Authors	Intervention	Country	Agriculture effect	Environmental effect
Technology Adoption	Behrer, A. (2019)	National Employment Guarantee Act	India	No evidence of change in agricultural productivity	Increase in fires
Technology Adoption	Carreira, I., Acosta, F., and J.P. Pessoa (2024)	Exposure to GM soy seed	Brazil	Increase in soy cultivation	Decrease in forest
Technology Adoption	Bridle et al. (2020)	Various	Global	Potential increase, though often limited by external constraints	Limited direct environmental impacts observed
Technology Adoption	Holden (2019)	Farm Input subsidies	Africa	Review paper: Increased agricultural productivity	Review paper: Potential negative impacts if not managed sustainably
Technology Adoption	Pelletier et al. (2020)	Maize intensification	Zambia	Improve productivity	Reduced deforestation
Technology Adoption	Stevenson et al. (2013)	Green Revolution	Global	Enhanced crop yields substantially increased global food production	Prevented extensive land conversion, conserving natural ecosystems
Technology Adoption	Suri and Udry (2022)	Various	Sub-Saharan Africa	Review paper: Increase in food production with proper implementation	Review paper: May reduce land expansion