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The Environmental Impacts of Agricultural Intensification

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Abstract

Agricultural intensification is necessary to meet growing global food demand, but it has potential environmental costs. Some activities associated with intensification, including increased use of fertilizer and other chemical inputs, are documented to have direct negative impacts on air and water quality, soil fertility, and other parts of the ecosystem. The effect of intensification on the amount of land under cultivation is more complex because it depends on accompanying policies, factor markets, and the spatial and temporal scale of analyses. The impact of these feedbacks and indirect effects on land conversion is relatively well studied, but they may also shape the impact of intensification on other environmental outcomes. A review of the literature helps organize existing results and suggests potential approaches to mitigating the environmental costs of agricultural intensification. Further research is needed to understand causal mechanisms and inform policies designed to meet production goals while minimizing environmental costs.

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1 Introduction

If global population and food consumption trends continue, by 2050 the world will need 60 percent more food than is available today, placing added pressure on the natural resources involved in food production (FAO 2019). Agricultural intensification, commonly understood to imply an increase in aggregate yield per unit of land area (Rudel et al. 2009; Ewers et al. 2009; Phelps et al. 2013; Villoria et al. 2014), is often seen as a way to increase productivity and meet a growing global demand for food, while conserving land for nature. Historically, periods of technological innovation, rapid intensification, and yield improvements, such as the Green Revolution, were hailed as progress toward meeting the rapidly growing world demand for food. More recently, however, new scrutiny has raised concerns about the environmental costs of agricultural intensification, including effects on land use change, air and water, soil fertility, biodiversity, and disease transmission. Understanding the impacts of intensification on these environmental outcomes is important for ensuring that global food demand is met in environmentally sustainable ways.

Some of the costs or benefits of intensification practices accrue to the farmer or landowner, and others—known as externalities—do not.[1] When intensification directly influences the future productivity of farmland, the farmer should incorporate expectations of this productivity change into the decision of how and whether to intensify. The outcome of intensification, in that case, is realized as a private cost (or benefit) to the farmer and does not generate a direct externality. While not all externalities are environmental (e.g., learning externalities), this review focuses on environmental externalities.

The outcome of intensification—an increase in aggregate yield per unit land area—is often driven by changes in inputs such as fertilizer or high-yielding crop varieties. It is important to distinguish between environmental impacts that arise from changes in the outcome and those that arise from the inputs that drive the intensification process itself. Both may be important. For example, yield improvements may impact the environment through changes in profitability or relative prices (Villoria et al. 2014). Inputs, such as fertilizer, may also have important environmental impacts (regardless of the net effect on yields). This review includes both drivers of intensification-associated impacts and attempts to distinguish between them throughout.

Both the sign and the magnitude of impacts on the environment as a result of intensification are ambiguous and vary when examined at different temporal and spatial scales.[2] Intensification generates direct effects on environmental outcomes as well as more complex indirect effects. The process of intensification is typically driven by increased use of fertilizers and other chemical inputs, which have been connected to negative environmental outcomes including air and water pollution (Tang et al. 2014), reduced soil fertility (Tsiafouli et al. 2015), destruction of biodiversity (Karp et al. 2012), and increased propagation of disease (Jonsson et al. 2012; Pulliam et al. 2012).

The effects of intensification on the amount of land under cultivation are more complex. Agricultural intensification could lead either to decreased land under cultivation owing to higher crop yields or to increased land under cultivation owing to higher profitability (Villoria et al. 2014), demand increases, and output price responses (Hertel et al. 2014). Various mechanisms determine which outcomes prevail in a

[1] We largely abstract from issues of land tenure, except where explicitly noted, and use the term "farmer" to refer to the person who makes decisions about production and bears the costs and benefits of any impacts on the future productivity of her land.
[2] Note also that the unit of measurement is important. Environmental impacts may be quantified as absolutes (e.g., total greenhouse gas emissions), per-unit land area (e.g., GHGs per acre), or per unit of production (e.g., GHGs per kilograms of maize). Standardizing units of measurement across studies is beyond the scope of this review, but we acknowledge that findings may depend on these units in many cases.

given scenario: changes in productivity may increase total output (e.g., Paul et al. 2018), alter labor allocation (e.g., Ruben et al. 2006), or improve the productivity of capital (e.g., Anik et al. 2017), each of which may alter the impacts of intensification. Much of the literature on these mechanisms focuses on land use and the corresponding greenhouse gas (GHG) emissions, but similar feedbacks may extend to other environmental outcomes as well.

Policies and markets can also mediate the impacts of intensification (Lee et al. 2006). These can be harder to study in a reduced-form partial equilibrium framework. General equilibrium models incorporate a larger set of conditions and outcomes—including reallocation of inputs and market responses—and impacts over different temporal and spatial scales. The interplay of these mechanisms and the circumstances under which each dominates determines whether intensification has a net positive impact on the environment.

Advances in empirical causal inference and improvements in measurement of environmental impacts have improved our understanding of the links between agricultural intensification and environmental outcomes. However, well-identified causal evidence and studies that isolate the individual mechanisms driving those outcomes remain scarce. The objective of this review paper is to revisit the literature that attempts to uncover causal relationships and highlight the major knowledge gaps in linking intensification to environmental outcomes.

The remainder of this review is organized as follows. The next section, following this introduction, examines the theoretical foundations of our understanding of how intensification affects land use and other environmental outcomes. The third section explores the empirical evidence on the direct effects of intensification on environmental outcomes. The fourth section discusses a number of channels that complicate direct effects, including the role of mediating mechanisms such as markets and policy, general equilibrium effects, and the temporal or spatial scale of the analysis. The fifth section reviews opportunities for minimizing the negative effects of intensification, and the final section concludes with a discussion of directions for future research.

2 Conceptual Framework

This section discusses the theoretical literature, and in doing so lays out a conceptual framework that will loosely guide subsequent sections. Agricultural intensification is often characterized by increased use of production inputs such as fertilizer and high-yielding crop varieties. Some of these inputs generate direct environmental externalities, such as runoff from chemicals. The magnitude of these direct externalities on water quality or quantity, air quality, or biodiversity, for example, is largely an empirical question; their theoretical impacts tend to be unambiguously negative.

Whether intensification increases or decreases the use of another important agricultural input, land, is a more hotly debated topic. Several economic models have examined the links between intensification and land use. Most prominently, Borlaug’s hypothesis suggests that increasing agricultural productivity per unit area will decrease the need for agricultural expansion, reducing pressure on adjacent land and resulting in less land being converted from a natural state for agricultural production. Contradicting Borlaug’s hypothesis is an alternative theory known as Jevon’s paradox, in which an increase in the productivity of one input (e.g., agricultural land) leads to increased, rather than decreased, overall use of that input (Ceddia et al. 2014). In the case of agricultural intensification, increased yields generate an associated increase in profitability, thereby creating an increased demand for agricultural land. The paradox may emerge when the magnitude of the scale effect is greater than the efficiency gains driving Borlaug’s hypothesis.

A theoretical framework that accommodates both Jevon's paradox and Borlaug's hypothesis can help explain the factors that make outcomes consistent with one theorized view of the world versus the other. For example, Borlaug's hypothesis often is associated with a fixed demand for food, while Jevon's paradox is more relevant for price-elastic markets (Hertel et al. 2012; Angelsen and Kaimowitz 2001). Usually, however, the impact on land use is uncertain, as it depends on factors both in the region undergoing intensification and in the rest of the world.

Hertel et al. (2014) develop an analytical framework reconciling these two views to explain when agricultural intensification leads to expansion or contraction in the amount of land under cultivation. When a region undergoes agricultural intensification, the percentage change in global land use is expressed as a weighted combination of the land use change in the region and the rest of the world. The framework reflects that when suppliers in the intensifying region become more productive, world prices fall. This price drop results not only in an increase in global demand for crops but also in reduced production from suppliers in the rest of the world. The relative magnitude of this output expansion in the innovating region and the production decrease in the rest of the world is described by the excess demand elasticity. It is determined by the price responsiveness of world demand and the supply response in the rest of the world, as well the relative share of the intensifying region in global production. Excess demand is more likely to be elastic when world demand is price responsive, the rest-of-world supply response is relatively large, and the innovating region has a low share of global production. When these conditions hold, the region undergoing intensification should experience an increase in agricultural land under cultivation. This result reflects the fact efficiency gains due to increases in yield are counteracted by the increased demand for crops and decreased rest-of-world outputs, leaving the door open for further agricultural expansion. However, it is more difficult to make concrete claims about the net *global* land use change caused by intensification. The overall environmental cost may therefore depend in part on whether the area undergoing intensification is particularly environmentally sensitive or not.

In spite of these conceptual challenges, Hertel et al. (2014) identify factors likely to contribute to net increases in agricultural land use in response to intensification, based on the framework summarized above. In addition to elastic excess demand, the relative magnitude of agricultural expansion in the innovating region must exceed that of contraction in the rest of the world in order for Jevon's paradox to dominate. If global food demand is price responsive and pre-intensification yields in the intensifying region are relatively low, expansion in this region will be magnified. This framework emphasizes the importance of understanding the fundamental economic parameters underpinning the regional and global supply of and demand for agricultural land.

Land use change often results in additional environmental impacts. In other words, intensification can affect other outcomes indirectly through its effect on land use. For example, the IPCC (2019) estimates that 23 percent of total anthropogenic GHG emissions are derived from agriculture, forestry, and other land use. If agricultural production uses both land and environmentally harmful inputs, such as fertilizers or pesticides, an increase in land under agricultural production may mechanically result in more damage to water or air quality, for example. To the extent that intensification results in an expansion of land under production, it will generally have negative impacts on the environment owing to habitat loss, GHG emissions, and changes to local hydrology and ecosystems.

Our review largely ignores spatial heterogeneity in the environmental impacts of land use. This is clearly a simplification of reality: different plots of the same size can generate very different impacts depending on their location, the use of neighboring plots, and other factors. Factors that affect the relative benefits of sparing a particular patch of land include its potential for biodiversity (Nunes and Van den Bergh 2001) and other ecosystem services, such as provision of fresh water (Keeler et al. 2012) and pollination services (Winfree et al. 2011). The existing state of the ecosystem in which a parcel sits plays a role as well. Ecosystem tipping points, for example, may influence which parcels of land should be prioritized for conservation. These tipping points describe situations in which modest environmental changes can cause disproportionately large changes in ecosystem properties (Laurance et al. 2011). More damage is likely to occur if the land that enters production is located in an ecosystem that is in danger of approaching an ecological tipping point. Intensification could, for example, result in decreased overall land under cultivation but have relatively undesirable outcomes on other fronts owing to conditions in and around the specific patches of land under cultivation. These considerations have been explored in the ecosystem service and contingent valuation, biology, and ecology literatures but generally fall beyond the scope of this review.

Although land use change is generally the outcome of interest in the Borlaug-versus-Jevon debate in the context of agricultural intensification, other environmental outcomes may be similarly affected by indirect effects, such as changes in prices. For instance, efficiency gains from intensification may be tempered by price responses in complementary inputs or supply responses in other regions. These effects could plausibly result in environmental impacts such as pollution due to additional fertilizer use or degradation of soil. In addition, indirect channels affecting both land use and the use of other inputs or affecting other environmental outcomes may be important. For example, higher incomes from intensification may lead to cleaner production technologies or increase the demand for health. Further theoretical innovation is needed to illustrate these potential channels.

3 Direct Effects of Agricultural Intensification on Environmental Outcomes

As described in the previous section, agricultural intensification can, in theory, have both positive and negative direct effects on the local environment. However, the current empirical literature points toward a range of suggestive (predominantly correlational) evidence linking agricultural intensification to negative environmental outcomes.[3] This section focuses on direct effects; later sections return to indirect effects, including those that arise in general equilibrium. While land-use change and air and water pollution are the most researched areas of impact, agricultural intensification can affect many facets of the environment. This section is organized by impact area, broadly categorized into land use change, air and water pollution (including GHGs), biodiversity, soil fertility, and other factors including animal-borne diseases and human-wildlife conflict. We simplify a number of important considerations, including nonlinearities and irreversibilities that arise for some types of externalities. We leave these as topics for future discussion.

Identifying causal links between intensification and the environment is challenging, primarily because of the complexities and dynamics of natural systems. While we prioritize causal evidence when available, correlational findings can provide an important starting point for further scrutiny.

[3] For the purpose of our review, we classify evidence as causal if it clearly establishes the observed environmental outcome as a result of intensification, rather than only a co-occurrence. However, most studies in this literature detail correlational relationships and cannot address concerns about interpretation because they omit other factors that may be correlated with intensification decisions and that also impact the outcome of interest. These studies often provide valuable insights and are included where relevant.

3.1 Land Use Change

Land use change is perhaps the environmental impact area with the most causal evidence establishing agricultural intensification as a driving force. Not only is land use an impact itself, but it is also associated with a variety of additional environmental impacts. For example, the conversion of native ecosystems into agricultural land leads to increased greenhouse gas emissions (IPCC 2019) and is a major driver of species loss (e.g., Pimm and Raven 2000; Medan et al. 2011; Newbold et al. 2015). Expansion of agricultural activity may also lead to increased pollution levels, whether due to increased use of inputs or a loss of valuable ecosystem services (e.g., Ouyang et al. 2014; Rodriguez-Galiano et al. 2014; Polasky et al. 2011; Short 2013). To our knowledge, these effects on ecosystems and pollution have not—with the exception of GHGs—been directly linked to land use change due to agricultural intensification.

Much of the empirical research on agricultural intensification and land use change ties into the Borlaug-versus-Jevon debate and establishes agricultural intensification as the driving force behind expansion or contraction of forest and farmland. The empirical results of these studies suggest the presence of a combination of the two theorized effects. For instance, Abman and Carney (2016) show that areas in Malawi with a high proportion of individuals of the same ethnicity as the president received more fertilizer subsidies and increased their hybrid maize yields. As a result, these areas saw significantly less deforestation than did areas with other predominant ethnicities, in support of Borlaug's hypothesis. Fisher and Sively (2007) also take advantage of a government subsidy program and find support for Borlaug's hypothesis in a localized setting in Malawi's Miombo woodlands. Their econometric results show that households that received hybrid maize seed and chemical fertilizer had lower levels of commercial forest extraction than nonrecipient households. They also find no measurable effect of seed or fertilizer receipt on forest-clearing decisions, suggesting the program raised agricultural output without encouraging agricultural expansion.

3.2 Air and Water Pollution

The current literature points toward net negative effects on air and water pollution as a result of agricultural intensification. Multiple studies highlight that gains in yields are driven by increases in the use of certain inputs such as fertilizers and pesticides, which are associated with worsening water quality (Tang et al. 2014 Lange et al. 2014; Stehle and Schulz 2015). While the magnitudes of these effects vary across studies (e.g., Neill et al. 2017), there appears to be a consensus on the negative impacts, particularly when input use is measured in aggregate terms or per area under production, as opposed to per unit of output. Other features of intensification include increased livestock stocking rates (Strokal et al. 2016 Smith et al. 2013), the use of harvest fires (Rangel and Vogl 2019), and fertilizer agrichemical use (Brainerd and Menon 2014, all of which have been shown to have detrimental effects on air and water quality.

A separate literature has documented the negative effects of air and water pollution on human health (e.g., Neidel 2004; Currie et al. 2009), worker productivity and firm profits (e.g., Hanna and Oliva 2015; He et al. 2019), and a number of other economically important outcomes (Heblich et al. 2019; Khanna et al. 2019; Chen et al. 2017). Where intensification lowers air quality and water quality, similar impacts are likely to arise, though relatively few papers have documented the causal chain from intensification through to human health impacts. In some cases, agricultural practices or inputs have been linked to health impacts. For example, Rangel and Vogl (2019) show that exposure to smoke from sugarcane harvest fires in Brazil affects infant health. Another example is Brainerd and Menon (2014), who show that agrichemical use associated with the Green Revolution in India led to higher levels of water pollution and ultimately to worse health outcomes for children.

Agricultural intensification can affect GHG emissions in two opposing directions, resulting in an ambiguous net effect. Agriculture—through on-farm activities and land use change—generates between one-quarter and one-third of global GHG emissions (Braimoh et al. 2016). Fertilizer application and production are large emitters of GHGs, but analogous to the discussion on land use change, higher-yielding crops may result in a lower amount of land under agricultural production, decreasing aggregate GHG emissions. Hickman et al. (2015) find that agricultural intensification increases crop yields without immediate large increases in nitrous oxide (N_2O) emissions if fertilizer application rates remain at or below a threshold level. If less land is brought into production as a result of intensification, then the use of the unconverted land matters: if it is restored to natural habitat, emissions may even decline (Lamb et al. 2016).

3.3 Soil Fertility

The effects of agricultural intensification on soil fertility are often internalized into farmer decisions, but may exclude the externalities imposed by changes in soil quality on other ecosystem services. Evidence on this topic remains scarce. A few studies employ agronomy experiments to demonstrate that fertilizer use may reduce soil resilience to stress and important ecosystem functions (Postma-Blaauw et al. 2010, 2012). However, it is difficult to interpret agronomy experiments as causal evidence of the impacts of agricultural intensification, which is accompanied by changes in many other aspects of production and market factors. In addition, impacts on soil fertility may contribute to desertification or land degradation, which in turn may affect the recruitment of new land into production, particularly in arid farming regions. An understanding of these impacts requires further research into the effects of intensification on soil quality that are not internalized into farmer decision-making. In addition, it remains unclear to what degree farmers account for soil fertility impacts in their production decisions.

3.4 Biodiversity

Several recent studies have established a correlational relationship between intensification and decreases in biodiversity. Potential channels include the use of inputs, such as fertilizer or pesticides that harm ecosystems and organisms, and increased density of crops that crowd out the habitat that exists in less intensively used farmland. The literature shows a clear relationship between agricultural intensification and a decline in amphibian presence and pond habitat (Arntzen et al. 2017). Much of this evidence is subject to concerns about omitted variables: changes in other factors that are correlated with farmer intensification decisions and also affect amphibian presence. For example, new road construction might increase the likelihood of intensification if it lowers transportation costs while also affecting amphibian populations directly. Analysis that omits road construction would overstate the impact of intensification on amphibians. Several studies establish associations between agricultural intensification and other measures of biodiversity (e.g., Cleary et al. 2016; Karp et al. 2012), but we are unaware of any plausible causal evidence addressing the direct impact of intensification on species biodiversity.

3.5 Other Impacts and Research Priorities

Some studies have linked increased emergence of disease with livestock and agricultural intensification (e.g., Jonsson et al. 2012; Pulliam et al. 2012). Jones et al. (2013) review the evidence and conclude that agricultural intensification and environmental change were associated with an increased risk of zoonotic, or animal-borne, disease emergence. This area of impact, though newly relevant with the global COVID-19 pandemic, is difficult to causally identify and requires further research.

Intensification may have impacts on the quantity of surface water and groundwater. In the context of the Green Revolution in India, researchers have noted that intensification has been accompanied by overexploited and declining water tables in many places across the country (e.g., Foster & Rosenzweig 2008; Singh 2000; Bose et al. 1998), but we have not found any plausibly causal empirical studies.

The above two impact areas, along with several others discussed in this section, are in need of further research. Much of the literature cited in the preceding subsections comes from the ecology and biology literatures. This is due in part to the natural dynamics of intensification that are of interest in their own right. Greater attention by social scientists can help ensure that farmers' decisions are accounted for in these studies and that causality is taken seriously. Of course, this goal requires exogenous variation in intensification, which is rare and places a limit on the potential for rigorous causal research.

4 Moderating Factors and Indirect Effects

The previous section focused on the direct effects of agricultural intensification on environmental outcomes. Here, we turn to the moderating role of policy and markets, including price adjustments in general equilibrium. We also discuss the importance of spatial and temporal scales for measuring impacts. For example, effects in the short run may have very different magnitudes—and even different signs—than effects in the long run.

4.1 Policy

Public policy can allow governments to minimize the environmental harms from agricultural intensification, at least in expectation. A number of studies investigate whether policies can induce agricultural intensification and how those affect the environment; fewer have studied whether policy can also moderate the impact of intensification on environmental outcomes. The literature reviewed below highlights the potential of government policies to minimize the negative impacts of intensification. Existing evidence suggests that this potential depends on both the strength of government and the degree to which it prioritizes environmental quality.

Policies incentivizing agricultural intensification may affect environmental outcomes, given the evidence in the previous section, and these outcomes may depend on the specific policy instrument used. Cohn et al. (2014) use an economic optimization model of global land use to explore two hypothetical Brazilian policies: a tax on cattle from conventional pasture and a subsidy for cattle from semi-intensive pasture. They model, from 2010 to 2030, global agricultural outcomes, land use changes, and GHG abatement under each policy. They find that both the tax and the subsidy allow beef demand to be met with less total pastureland and result in considerable conservation of forests and abatement of GHGs. The tax, however, delivered more forest conservation than the subsidy because it stimulated a larger increase in world beef prices, resulting in reduced beef consumption worldwide. This modeling approach highlights the importance of accounting for general equilibrium effects, which we return to in the next section. Like Cohn et al. (2014), other model-based papers have compared the environmental impacts of different policies to promote intensification (e.g., Paul et al. 2018; VanWey et al. 2013) and clearly show that the type of policy instrument can influence the impacts of intensification.

Various policy mechanisms have been considered to facilitate agricultural intensification and mitigate the potential harms. For example, Maertens et al. (2006) show that access to improved irrigation systems for paddy rice cultivation in Indonesia reduced agricultural expansion at forest margins while adoption of hand tractors (a labor-saving technology) increased pressure on forests. This study highlights the interplay between policy and markets for other inputs to the agricultural production process, which we turn to next. Important determinants of the success of specific interventions include the role of labor market conditions, market access, and stakeholder participation (Lee et al. 2006).

Others have focused on the role of governance, rather than the specific policy instrument, in moderating the effect of intensification on environmental outcomes. For example, Ceddia et al. (2014) find that intensification leads to a spatial expansion of agriculture when broad governance scores are high. In contrast, intensification leads to a spatial contraction of agriculture, signaling a sustainable intensification process, when environmental aspects of governance are high. This suggests that environmentally minded governance has the potential to reduce the negative effects of intensification.

4.2 Factor Markets

Productivity gains from intensification not only increase output but may affect the demand for labor and change the productivity of capital. These changes may in turn affect environmental outcomes. Few studies address how intensification affects these input markets, and even fewer address how adjustments in factor demand or productivity can impact environmental outcomes.

Increased demand for inputs and increased access to complementary inputs for intensification affect the environment. In Brazil, for instance, the expansion of rural electrification led to increased crop productivity, causing farmers to expand farming through frontier land conversion (Assunção et al. 2019). At the same time, production shifted away from cattle ranching and into crop cultivation, which led to more native vegetation and ultimately a net decrease in deforestation. Burney et al. (2010) estimate the net effect of intensification on GHG emissions between 1961 and 2005. They find that increases in fertilizer production as well as its application led to an increase in emissions. However, resulting higher yields led to reduced agricultural expansion, and ultimately, 161 gigatons of avoided carbon emissions. This is an example of when efficiency gains underlying Borlaug’s hypothesis outweigh the market response and direct impacts of intensification.

Shaver et al. (2015) address coupled social and ecological outcomes of intensification in Costa Rica. Using an approach that combines field interviews and landscape metrics, they find that pineapple production concentrates land, labor, and financial resources. This may have a homogenizing effect on the agricultural economy in the study region, constraining farm-based livelihoods and negatively affecting biodiversity.

Introducing other mechanisms in the Borlaug-versus-Jevon debate can help interpret results. Garnett et al. (2013) examine the influence of land tenure, land use policy, cooperatives, and credit access on soy production in Brazil. Using county-level data, the authors provide statistical evidence that soy planted area and yields are higher in regions where cooperative membership and credit levels are high and where cheap credit sources are more accessible. They suggest that soybean production and profitability will increase as supply chain infrastructure improves. These results imply that other associated markets, such as financial markets (credit access in particular) can shape the response to intensification and its impacts on the environment.

As Garnett et al. (2013) note, factor markets may also be imperfect. Perhaps the best-studied instance of this is land tenure; where property rights are insecure, agricultural intensification may lead to very different impacts and adjustments. Kubitza et al. (2018) hypothesize that stronger land property rights could enable farmers to increase input intensity and productivity on already cultivated land, thus reducing incentives to expand their farms by deforesting additional land. This hypothesis is tested with data from a panel survey of farm households in Sumatra. Without land titles, these farmers are less likely to intensify and more likely to expand into the surrounding forest land to increase agricultural output. Ali et al. (2014) show that a land regularization program was associated with a large impact on agricultural investment and improvements in soil conservation outcomes. Improved tenure security provided by registration in the program allowed landowners, particularly women, to make longer-run investments.

4.3 General Equilibrium Price Adjustments

In addition to impacts on factor markets, which may in turn affect environmental outcomes, agricultural intensification may alter output prices and affect supply responses as discussed in section 2. Given the complexity of market adjustments in response to agricultural intensification, many researchers turn to computable general equilibrium (CGE) models. CGE modeling provides the advantage of supporting counterfactual scenarios, assuming the underlying relationships and parameterizations are hypothesized correctly. The modeling framework then allows different mechanisms to be teased apart by holding some markets fixed, for example, while allowing others to adjust.

Several studies use CGE models or related modeling approaches to address how agricultural intensification has affected land use change and GHG emissions. Using a general equilibrium model, Stevenson et al. (2013) find that germplasm improvement in the major staple crops during the Green Revolution saved an estimated 18 to 27 million hectares from being brought into agricultural production. The authors note that these estimates are orders of magnitude lower than simpler models that do not account for prices, consumption demand, and land use change, highlighting the importance of these feedbacks to the observed effects of intensification. Jones and Sands (2013) similarly simulate the global market impacts of intensification on agricultural output across 15 global regions and the resulting implications for non-CO_2 emissions. They find that productivity growth can reduce global methane (CH_4) and NO_2 emissions by 23 percent by 2034. Like the above studies, various other papers find that Borlaug's hypothesis dominates in certain circumstances (e.g., Lobell et al. 2013; Bashaasha et al. 2001; Gockowski and Sonwa 2011).

4.4 Temporal and Spatial Scales

Agricultural intensification may have differing impacts on environmental outcomes at different spatial scales, as discussed in section 2. General equilibrium modeling can be used to examine the impacts of intensification at differing spatial scales, as price and supply responses vary across regions and countries. Villoria et al. (2013) investigate two potential scenarios of technological change for oil palm in Indonesia and Malaysia with a computable general equilibrium model. They find isolated total factor productivity (TFP) growth in oil palm in Indonesia and Malaysia is likely to lead to slight regional deforestation, although globally it may encourage forest reversion. As technological progress becomes global, there is net reversion both locally and globally. Correspondingly, emissions can ultimately decline. Hertel et al. (2012) model the impact of a 1 percent regional increase in TFP on land use regionally and globally. They find that agricultural land use in the innovating region increases in all cases but that net global impacts depend on where the productivity increase occurs. Global agricultural land use increased with the TFP boost in Sub-Saharan Africa but decreased when Latin America, South Asia, or East Asia/Pacific underwent intensification. Relatively low yields and elastic land supply in Sub-Saharan Africa contribute to the projected increase in global agricultural land use after intensification.

Villoria (2019) estimates the effect of agricultural technological progress at both the country and global levels. After accounting for the interdependence of national supply responses, the study provides estimates showing that TFP is positively correlated with cropland expansion in most countries. Worldwide, however, TFP has increased conservation. These seemingly contradictory findings are attributed to changes in production patterns stemming from international market interactions.

It is possible to see differential environmental outcomes at smaller scales as well. Using a CGE model in the case of Brazil, Gonçalves da Silva et al. (2019) find that Borlaug's hypothesis holds in the case of increases in livestock productivity, leading to reduced deforestation. In the case of crop productivity increases, however, agricultural land use rises as per Jevon's paradox. The relative benefits of intensification also vary by biome. For instance, the Amazon biome benefited from large reductions in the expansion of cropland and pasture, but some other biomes saw minimal impacts or even an expansion of cropland.

In some cases, intensification may result in different long- versus short-run environmental outcomes. Few studies provide long-run empirical evidence, but there are some notable exceptions. Rodriguez Garcia et al. (2019) examine the relationships between agricultural intensification, Borlaug's hypothesis, and Jevon's paradox on cropland area and productivity. The authors attempt to disentangle the long-run and short-run causal relationships by using fixed-effects models and a cointegration approach. In the short run they find support for Borlaug's hypothesis in rich countries but see evidence of Jevon's paradox in poor countries. In the long run, though, Borlaug's hypothesis seems to hold for both low- and middle-income countries. Caviglia-Harris (2018) finds that cattle production initially increases demand for newly cleared land, but further intensification then decreases such demand. This result suggests support for Borlaug's hypothesis over medium to long time horizons. Meanwhile, intensification related to dairy production was related to reduced demand for pasture in both the short and long run, lending further support to Borlaug's hypothesis as dominating effect in this setting.

5 Mitigating the Negative Effects of Intensification

In order to meet global food security goals while minimizing environmental and social harm, investigations into the successes and shortcomings of agricultural intensification will be a priority moving forward. Understanding the relationships described throughout this review, between increased yields and the inputs, policy structures, and other mechanisms that shape the effect of intensification on the environment is a necessary component to mitigating the potential harms of intensification moving forward.

In some cases, fixing missing markets provides an important first step. Inefficiencies in the implementation of agricultural intensification schemes can fail to increase productivity or even result in unintended consequences. Using a randomized control trial, Chakravorty et al. (2019) provide causal evidence that alternate wetting and drying—a water conservation technology—saves water and increases profits when farmers pay a marginal price for water but fails to do so when they pay fixed seasonal charges. This paper demonstrates the importance of pricing of natural resources for minimizing the negative impacts of intensification.

Policies aimed at specific environmental goals may mitigate harm while supporting intensification. One example of this, the Priority List, an anti-deforestation strategy in Brazil, was evaluated by Koch et al. (2019) with a difference-in-differences approach. The authors find that the policy may have both reduced deforestation and increased productivity. Policy-induced decreases in the value of clearing land led farmers to reallocate investments into farming capital and away from deforestation. Another paper by Gibbs et al. (2019) finds that both Brazil's Priority List and G4 Cattle Agreements helped boost cattle productivity, while the G4 Agreement also boosted investment in inputs and capital. These studies show that there are not necessarily always trade-offs between increased productivity and desirable environmental outcomes.

Lobell et al. (2013) model global agricultural trade and land use to examine different climate adaptation scenarios. The results show that investing in productivity improvements in developing areas, while less costly, may have little net effect on GHG emissions. This is because production gains are offset by greater rates of land clearing in those regions, which are low yielding and abundant in land. Adaptation investments in high-yielding, land-scarce regions such as Asia and North America are more effective for mitigation. While these claims are not causal, the study emphasizes that investment decisions related to productivity growth may have different global outcomes depending on the location of these investments. Accounting for differential outcomes based on these investment decisions may help to maximize benefits of intensification.

Further insight into mechanisms and potential mediating policies is needed to understand how policy can shape the environmental impacts of intensification. For example, as described above, Ceddia et al. (2014) showed that intensification led to a spatial contraction of agriculture when environmental governance indicators were high. Studies such as these help clarify how policy may influence the effectiveness of programs designed to promote intensification as well as the associated environmental outcomes. Combining this with research from the previously discussed settings may uncover systematic relationships that determine the overall net effect on the environment.

6 A Research Agenda

Although the potential environmental impacts of agricultural intensification have received substantial attention across a number of disciplines, important gaps in the literature remain.

The first major gap we identified is the lack of causal evidence for the direct impacts of agricultural intensification on environmental outcomes. Much of the literature that focuses on the direct environmental impacts of intensification is in the form of correlational evidence. This type of evidence can provide insight into which outcomes tend to occur with agricultural intensification, but it is not possible to establish these outcomes as the result of intensification itself. Most of the outcomes discussed in our review have little if any evidence establishing them as causal results of intensification, with the exception of land use change. Stronger causal evidence is necessary to establish intensification as the driving force behind many environmental outcomes including air and water pollution, biodiversity, soil fertility, and disease propagation.

Substantial attention has been focused on understanding the interplay of Borlaug’s hypothesis and Jevon’s paradox, but only recently have many of the theoretical underpinnings of these phenomena been formalized. Even with causal evidence beginning to emerge more frequently in this area, only a handful of studies address net effects from a causal inference standpoint. Villoria et al. (2014) note in their review of the effects of agricultural technological progress on deforestation that empirical evidence for Jevon’s paradox is much weaker than what the literature seems to accept. Our review supports this claim: the majority of empirical studies draw conclusions consistent with Borlaug’s hypothesis. However, we also share in the concern that many well-cited studies provide correlational rather than causal evidence, and we emphasize the need for further causal evidence on the net land use effects of agricultural intensification. With so few empirical studies available, it is unclear whether intensification will spare land or result in the expansion of agricultural land. This makes it difficult to determine how funding should be allocated and which policy interventions will be worthwhile, warranting further research.

Furthermore, future research should focus on understanding why outcomes are more consistent with Jevon’s paradox or Borlaug’s hypothesis in a specific setting. Determining which factors might contribute to the relative strength of mechanisms in play can help explain the conditions that would make intensification desirable. Findings from such a study may help to validate some of the theory that has been proposed.

Understanding how other mechanisms affect land use and GHG emissions outcomes is also an important area for further exploration. Policy mechanisms have been addressed to some extent, but there is still plenty of room to formalize theoretical bases and to provide causal evidence. The role of the reallocation of resources in determining land use outcomes is an underdeveloped area of the literature. There would also be value in exploring how other market failures, such as information failure or poorly defined property rights, affect which outcomes prevail.

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