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Cropland Restoration as an Essential Component to the Forest Landscape Restoration Approach—Global Effects of Wide-Scale Adoption

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ABSTRACT

Existing approaches and methodologies that investigate effects of land degradation on food security vary greatly. Although a relatively rich body of literature that investigates localized experiences, geophysical and socioeconomic drivers of land degradation, and the costs and benefits of avoiding land degradation already exists, less rigorously explored are the global effects of restoring degraded landscapes. The current scale of land degradation is such that the problem can be meaningfully addressed only if local successes are upscaled and a large number of landowners and land managers implement restoration activities. Significant global efforts to address degradation exist, but studies that evaluate the global benefits of these efforts generally do not account for global market forces and the complex web of relationships that determine the effects of wide-scale restoration on production and food security. This paper provides important insights into how a meaningful integration of crop production in restoration efforts could impact food production levels, commodity prices, food security, and other environmentally significant metrics.

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[1] For details, please visit https://ccafs.cgiar.org.

1. INTRODUCTION

International organizations have advocated in favor of halting land and forest degradation for decades. Land and forest degradation has multiple and complex impacts on the global environment through a range of direct and indirect processes that affect a wide range of benefits and people (Nkonya, Mirzabaev, and von Braun 2016). Estimates indicate that the global cost of land degradation due to land-use change and to the use of land-degrading management practices is about US$300 billion annually (Nkonya, Mirzabaev, and von Braun 2016). Between 1997 and 2001, an estimated loss due to global land-use changes was estimated at US$4.3–US$20.2 billion per year (Constanza et al. 2014; Suding et al. 2015). It is also estimated that if the current pace of land degradation were to continue over the next 20 years, it could reduce global food production by as much as 12 percent and increase the price of some commodities by as much as 30 percent (IFPRI 2012).

Even though land and soil degradation is widespread and occurs globally (Nkonya et al. 2011), research and projects have focused mostly on arid, semiarid, and dry subhumid areas, with particular attention paid to the susceptibility of such ecosystems to desertification (Lu et al. 2007). Research and on-the-field activities to prevent forest degradation and promote restoration have instead concentrated mostly on tropical forests, where important changes are taking place. Three major forces have driven the loss of tropical forest in the recent past: conversion to other uses, mostly for farmland (Gibbs et al. 2010; Hansen et al. 2013) and mining (Edwards, Sloan, et al. 2014); degradation of remaining forest due to logging and fires (Edwards, Tobias, et al. 2014; Cochrane 2003); and fragmentation (Laurence et al. 2002). The magnitude of these changes is important: approximately 100 million hectares of tropical forest were converted to farmland between 1980 and 2012 (Gibbs et al. 2010; Hansen et al. 2013), and selective logging affected about 20 percent of tropical forests between 2000 and 2005 (Asner et al. 2009). Only a minority of the forests remains as intact forest landscape2 (Potapov et al. 2008). Hansen et al. (2011)

[2] Intact forest landscape is defined as areas between 500 hectares and 10 square kilometers wide with no settlements or industrial logging.

reported that across the world, 24 percent of the existing tropical forests are intact, 46 percent are fragmented, and 30 percent are degraded. Cropland expansion and increase in yield productivity in tropical regions have occurred at the expense of tropical deforestation (Henders, Persson, and Kastner 2015). Tropical deforestation, in addition to biodiversity loss and soil degradation, is also responsible for significant amounts of greenhouse gas emissions (Henders, Persson, and Kastner 2015).

These figures provide a sense of the scale of land degradation and its global effects. The magnitude of the problem is such that it can be meaningfully addressed only if large numbers of landowners and land managers become involved in restoration activities.

Not surprisingly, the international community has been engaged in halting degradation and possibly restore degraded land for decades. The United Nation Convention to Combat Desertification (UNCCD) established in 1994, has led international efforts that aims at reversing and preventing desertification and land degradation. More recently (September 2011) the Bonn Challenge was launched and later extended with the New York Declaration on Forests of the 2014 UN Climate Summit. The Bonn Challenge is a global effort to bring 150 million hectares of the world's deforested and degraded lands into restoration by 2020 and 350 million hectares by 2030. It also provides an avenue to meet other existing international restoration commitments, including the CBD Aichi Target 15, the UNFCCC REDD+ goal, and the Rio+20 land degradation neutrality goal and possibly the Sustainable Development Goals and the climate change mitigation and adaptation goals in the Paris Agreement. Given the significant role that the Bonn challenge plays in addressing degradation globally, we use its restoration commitment (move 350 million hectares of degraded and deforested land into restoration by 2030) as a benchmark for this study.

However, significant forces have impeded the progress and the achievement of land and forest restoration goals, even though actions that transform degraded lands into functional landscapes are less costly than no action (Chazdon et al. 2017). Large-scale restoration is not normally practiced by communities living in degraded landscapes, even though localized, demand-driven success stories do exist (Keil, Zeller, and Franzel 2005; Kabwe et al. 2016; Reij, Tappan, and Smale 2009; Lambert and

Ozioma 2012; Garrity et al. 2010; Brown et al. 2009; Matocha et al. 2012; Calle, Z., et al. 2013; Winterbottom et al. 2013; Deichert, Krämer, and Schöning 2014). Many national forest strategies have focused exclusively on how to best manage and protect intact areas of forest; when national forest programs and strategies have recognized restoration as a priority, they have tended to concentrate their restoration activities on the establishment of industrial plantations. In doing so, they have often alienated local communities and have not received the support needed to succeed (Rietbergen-McCracken, Maginnis, and Sarre 2007). Even in successful cases, such as the ones reported by Lamb, Erskine, and Parrotta (2005), key limitations are found in the high costs and the limited supply of significant volumes of commercially useful goods (Erskine 2002). Widespread adoption of restoration practices is possible only if landowners, farmers, smallholders, and land managers benefit from it and only when restoration programs have stakeholder support (Sengupta, Maginnis, and Jackson 2005).

In answer to these long-standing problems are approaches based on the management of landscapes. The forest landscape restoration approach, in particular, provides a framework that implements sustainable forest management, while creating a substantial role for agriculture. The active role of agriculture in such restoration efforts is expected to induce a direct participation of communities, thereby reducing the observed opposition to large-scale restoration projects (Rietbergen-McCracken, Maginnis, and Sarre 2007). Given the key role that agricultural land and crop production plays in the forest landscape restoration approach, this paper sets out to explore the potential effect of agricultural involvement in restoration efforts on agricultural production, food prices, and food security.

The results of this study reveal that the full inclusion of crop production in the forest landscape restoration approach could produce large-scale, worldwide benefits for food security and therefore facilitate a wide uptake of restoration practices and the implementation of large restoration projects. The positive impacts are multifaceted and significant in size: a reduction in malnourished children ranging from three to six million; a reduced number of people at risk of hunger, estimated to be between 70 and 151 million; reduced pressure for expansion of cropland; increased soil fertility; and reduced greenhouse gas emissions. As impressive as these results are, the limits of the modeling employed indicate that these are still underestimates of the full potential of a widespread adoption of restoration practices. Countries supporting the Bonn Challenge and other restoration efforts should renew their efforts to ensure that current commitments are met to achieve the significant payoff of their investments.

2. THE FOREST LANDSCAPE RESTORATION APPROACH

The forest landscape restoration approach is a key principle underlying the Bonn Challenge. A key tenet of this approach is that a combination of forest and nonforest ecosystems, land uses, and restoration approaches can be accommodated within a landscape to achieve sustainable food production, improve the provisioning of ecosystem services, and promote biodiversity. Evidence shows that landscape-level interventions, such as restoration of riparian areas and wetlands to regulate water flows for agriculture or management of tree cover both within farmland and on surrounding landscapes, can enhance the provision of ecosystem services and support functionality of agriculture landscapes (Harvey et al. 2014). Farmers' managed natural regeneration in Burkina Faso, Niger, and Ethiopia was shown to promote the management of trees on farmlands, the conservation of soils and water (Reij, Tappan, and Belemvire 2005; Reij, Tappan, and Smale 2009; Garrity et al. 2010), the regeneration of natural vegetation with a consequent income diversification (Harvey et al. 2014), and enhancement of the adaptive capacity to droughts and the capacity to survive harvest failures. Agroforestry, home gardens, and silvopastoral systems in productive landscapes allow stakeholders to increase vegetation cover, protect forest remnants, generate wildlife habitats, and conserve and recover soil at landscape scale (Calle, A., at al. 2014). The establishment of native forest plantations, combined with subsistence and commercial crops (agroforestry) or cattle (agrosilvopastoral systems) on degraded agricultural lands, has been used as a tool in rural development projects worldwide (Montagnini 2001). Evidence from Malawi indicates how introduction of tree-based systems in agricultural landscapes is beneficial for soil fertility, higher crop yields, control of soil erosion, and restoration of soil organic matter and nutrients (Mungai et al. 2016).

The forest landscape restoration approach makes use of these experiences and aims at restoring ecological integrity, while also improving human well-being in deforested and degraded landscapes (Rietbergen-McCracken, Maginnis, and Sarre 2007). Restored degraded and deforested landscapes have the potential to enhance biodiversity and increase the resilience of vulnerable communities to climate shocks (such as floods and droughts), improve food and water security, and generate economic opportunities for local businesses and the national economy. Forest landscape restoration provides a framework to achieve these goals by (1) being future-oriented in restoring the functionality of landscapes from a degraded state (Box 1978; Wali 1992) but not necessarily returning it to a past state (Choi 2007); (2) striving to meet goals and objectives of landscape restoration as determined by stakeholders; and (3) addressing social, environmental, economic, and political challenges via iterative participatory negotiation, trial, and adaptation (Reed et al. 2016). The active role of agriculture in restoration efforts is expected to induce a direct participation of communities, thereby reducing the observed opposition to large-scale restoration projects (Rietbergen-McCracken, Maginnis, and Sarre 2007). An assessment of the opportunities to implement forest landscape restoration is currently underway in several countries, and forest landscape restoration is now being integrated into national, subnational, and regional commitments, plans, and strategies. Yet, the landscape restoration movement still struggles in becoming operational at a large scale due to lack of understanding of the complexities of landscapes and the perceived conflicts with the most pressing needs of some stakeholders (Chazdon et al. 2017).

3. ADOPTION OF RESTORATION PRACTICES

While the rationale underlying the forest landscape restoration approach appears sound, important issues related to the inclusion of agricultural area need to be investigated. On the one hand, the involvement of agricultural land in restoration efforts facilitates the engagement and active role of communities, helps with the implementation of restoration plans, and contributes to increasing long-term production and food security outlooks. On the other hand, important barriers may impede efforts to restore degraded agricultural land or to preserve its functionality. Although adoption rates of conservation and restoration measures often correlate with the estimated profitability of these activities, profitability of an alternative is necessary but often not sufficient for its adoption. Economic factors (for example, availability of labor force and mechanization) might make restoration a nonviable proposition under some conditions. Insecure property rights and land and tree tenure might make rural households unwilling or unable to invest in potentially risky restoration activities (Bewket 2007; Enfors and Gordon 2008; Shiferaw, Okello, and Reddy 2009; Teklewold and Kohlin 2011; Bryan et al. 2013; Mungai et al. 2016). Reforestation and restoration on land that has agricultural value (existing or potential) are also sometime unattractive options because of the high opportunity cost of locking land into these activities. Furthermore, management and governance issues due to differences in the size of landholdings, in landowners' economic and political power, and ultimately in individual preferences might limit uptake of such activities.

Several authors have pointed to the vicious circle of poverty and land degradation (Way 2006) and to the fact that poverty is often not only the result but also a cause of land degradation (Safriel and Adeel 2005). Nkonya et al. (2009) found that off-farm employment led to lower soil erosion and higher soil nutrient balances, suggesting that investments in agriculture alone might not be sufficient to address the problem of land degradation. Furthermore, it has been noted that poor farmers who have limited or no assets or access to credit tend to mine the land resource and do not adopt restoration practices, even when these would provide direct benefits (Nkonya et al. 2011). Property rights, their reliability, land ownership, and access to land in general are also widely considered important factors capable of either prompting or impeding investments in maintaining the land resource (Nkonya et al. 2011). Furthermore, sometimes the reality of a country's political economy might prevent the widespread adoption of restoration practices. In Malawi, for example, existing fertilizer subsidy programs might be in conflict with widely acknowledged beneficial use of agroforestry practices and of nitrogen-fixing legumes that partially replace the use of fertilizers.

Adoption rates of restoration and conservation practices can vary substantially according to the local geophysical and socioeconomic conditions. Keil, Zeller, and Franzel (2005) reported a 75.5 percent adoption rate of improved fallows among experimenting farmers in eastern Zambia. Similarly, for farmers in the Eastern Province of Zambia who trialed improved fallow, Kabwe et al. (2009) found that 73.6 percent adopted it. However, in a study on multiple agricultural technologies in Nepal (Floyd et al. 2003), the mean adoption rate was 31 percent. Similarly, a study on adoption of improved agroforestry technologies among contract farmers in Imo, Nigeria, had a mean adoption rate of 33.81 percent. Neupane, Sharma, and Thapa (2002), in their study on adoption of agroforestry in the hills of Nepal, found that 37 percent of the households from the project villages in Dhading District had not adopted exotic agroforestry species, and 51 percent of households from nonproject areas had adopted promoted agroforestry. Floyd et al. (2003) found that adoption was highest (40–60 percent) for the technologies of improved maize, wheat and grain legume varieties, improved tree fruit crops, and the planting of fodder trees. Intermediate levels of adoption (10–30 percent) were found for alternative technologies implemented on rice, finger millet, potato, and barley varieties; crossbreeding of cattle and buffalo; parasitic drenching of livestock; and improved forage species. Adoption levels were low (3–10 percent) for the technologies that targeted vegetables and vegetable seed production.

Some have argued that resources should be allocated to avoiding degradation and to sustainably managing landscapes that are still functional (Melo 2014). The value of preventing degradation is indeed well documented in the literature (Nkonya, Mirzabaev, and von Braun 2016). However, current rates of degradation on productive agricultural land pose serious risks to the agricultural production systems;

these risks are expected to be exacerbated by other factors, such as population growth, changing diets, and climate change. For this reason, we believe that restoration of degraded land is necessary, and we tailor the analysis to this particular problem.

4. MATERIALS AND METHODS

To characterize the involvement of agriculture in restoration efforts in terms of location and area and to assess the impact on production and food security of restoring degraded cropland, several datasets and models were used. The modeling required us to link and combine several datasets and modeling outputs: the assessment of global land degradation by Bao, Nkonya, and Mirzabaev (2016); the Spatial Production Allocation Model (SPAM; You et al. 2006); the Decision Support System for Agrotechnology Transfer (DSSAT; Jones et al. 2003); and the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT vers. 3.3; Robinson et al. 2015). The analysis is based on a comparison of a business-as-usual (BAU) scenario and two alternative scenarios generated by assuming different levels of involvement of agricultural land and different levels of adoption of conservation practices in crop production. The modeling develops as follows: The first step uses the Bao, Nkonya, and Mirzabaev dataset and the SPAM model to identify the land that is a candidate for forest landscape restoration. Once the candidate area has been selected, the three scenarios (BAU and two alternatives) are generated using input from the DSSAT model. The DSSAT crop model evaluates yields with current agricultural practices and yields with alternative management practices. The changes in yields are put into the IMPACT model to compute global changes in prices and ensuing effects on food security for 2010–2030.

The Location of Land Degradation

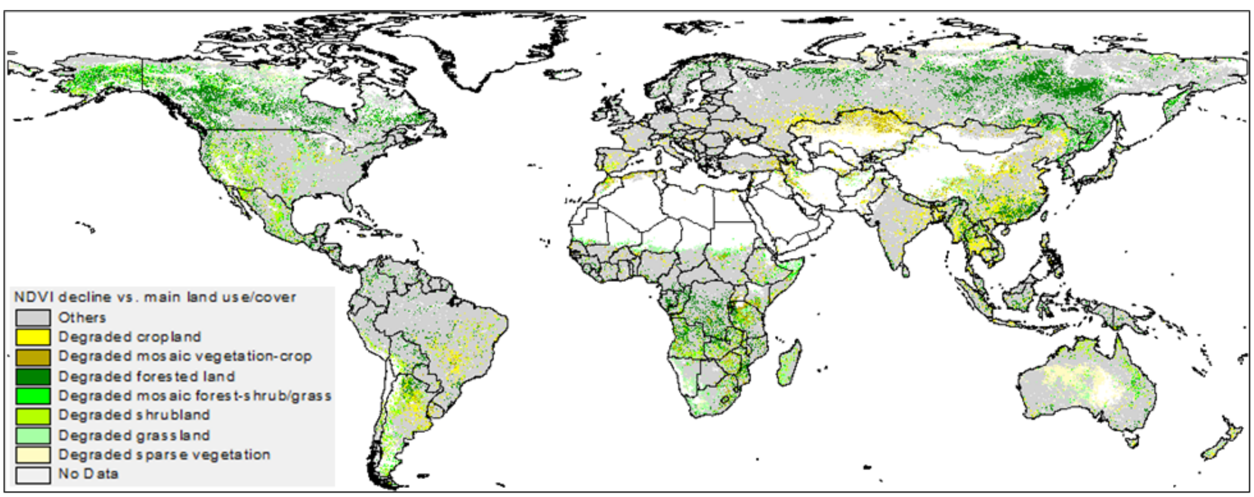
Bao, Nkonya, and Mirzabaev (2016) used long-term trends of biomass productivity as a proxy for land degradation and provided a global assessment of the areas subjected to a high degree of degradation (referred to as *hotspots*). These long-term trends are based on changes in the Normalized Difference Vegetation Index (NDVI) derived from satellite images for 1982–2006.

In a recent review of the prominent databases and methodologies used to estimate global degraded land undertaken, Gibbs and Salmon (2015) found that four approaches have been generally used: expert opinion, satellite observation, biophysical models, and inventories of abandoned agricultural lands. All approaches come with strengths and weaknesses; however, methods based on satellite observations have the advantage of being globally consistent, including all land uses and land covers, and being based on observed (rather than estimated or potential) changes in land productivity.

Bao, Nkonya, and Mirzabaev (2016) corrected for factors that could potentially confound the relationship between the remotely sensed vegetation index and land-based biomass productivity, such as the effects of interannual rainfall variation, atmospheric fertilization, and intensive use of chemical fertilizers. They found that degradation is widespread in all agroecological zones and affects about 2.6 million hectares, or about 29 percent of global land area.

Although substantial amounts of degradation are detected in forests (approximately 798 million hectares), 638 million hectares of degraded land are estimated to be in areas where crop production takes place. It is worth noting that significant amounts of degradation are also present in grasslands and shrublands (a total of 670 million hectares), with potentially significant negative impacts on the livelihoods and well-being of pastoralist communities.

Figure 4.1 Degradation hotspots by land cover and use types



Source: Bao, Nkonya, and Mirzabaev 2016.
Note: NDVI = Normalized Difference Vegetation Index.

Because Bao, Nkonya, and Mirzabaev (2016) identified areas with a high magnitude and extent of degradation (hotspots), they likely underestimated the full extent of degradation. Still, an analysis of the available datasets reveals the importance of addressing degradation in these areas. According to data collected by the Center for International Earth Science Information Network (CIESIN 2005) and from the World Development Indicators (World Bank 2016), approximately 15 percent of the world's population, 10 percent of the world's malnourished children, and 21 percent of the poor living in countries where agriculture represents a significant share of gross domestic product (GDP)[3] live in areas in which half or more of the land is classified as degraded by Bao, Nkonya, and Mirzabaev (2016).

The Location of Agriculture

The forest landscape restoration approach rests on the involvement of agriculture in restoration efforts. Therefore, identifying the location of agricultural land is essential to our modeling efforts. The location of agriculture is determined by augmenting the SPAM model with data from the global pasture dataset (Ramankutty et al. 2010). We combined these two datasets to create a global map of agricultural activities. The SPAM model uses biophysical crop suitability assessments, information regarding population density, and any other available prior knowledge regarding spatial distribution of specific crops or crop systems in order to spatially disaggregate subnational statistics of crop production and cropland data (for 2004–2006) into either 5-arc-minute or 0.5-degree grid cells. For each 0.5-degree SPAM grid cell (a square of approximately 50 by 50 kilometers at the equator), a database that catalogued the dominant management practices and input used by farmers (that is, varieties employed, application rates of inorganic fertilizers, organic amendment availability, and water management practices) was assembled. High-resolution data about climate scenarios, irrigation type, and soil properties were also cross-referenced for each grid cell. The global pasture dataset is a global assessment of the land used to support grazing animals; it is generated using satellite data from Moderate Resolution Imaging Spectroradiometer and Satellite Pour l'Observation de la Terre.

[3] In 2015, the world average contribution of the agriculture sector to GDP was 3.8 percent, according to the World Bank national accounts data (World Bank, 2016). A 5.0 percent threshold was chosen somewhat arbitrarily to consider countries that are significantly dependent on the agriculture sector; therefore, degradation on productive land has an important impact on livelihoods.

Table 4.1 reports the 20 most represented crops present in the area that Bao, Nkonya, and Mirzabaev (2016) identified as significantly degraded. The most important food crops are wheat, rice, and maize. Considered together, they represent approximately 42 percent of the cropland present in degraded areas. Most of the crops are annual crops; tree crops are present in less than 4 percent of the area assessed as degraded.

Table 4.1 The 20 most represented crops present in areas targeted for restoration

Crops	Area (million hectares)	Percentage of degraded area
Wheat	213,571,606	17.6%
Rice	148,169,854	12.2%
Maize	144,332,370	11.9%
Soybeans	92,422,785	7.6%
Barley	55,522,753	4.6%
Vegetables	44,510,843	3.7%
Sorghum	43,220,795	3.6%
Cotton	34,516,615	2.8%
Millet	30,057,826	2.5%
Other cereals	29,864,369	2.5%
Rapeseed	27,272,391	2.2%
Beans	26,909,393	2.2%
Other minor crops	22,797,034	1.9%
Sunflower	22,694,767	1.9%
Tropical fruits	22,670,564	1.9%
Temperate fruits	22,630,977	1.9%
Groundnuts	22,555,812	1.9%
Sugarcane	19,499,447	1.6%
Potato	18,695,121	1.5%

Source: Bao, Nkonya, and Mirzabaev 2016.

Simulated Scenarios

Barriers to adoption and the realities of each country's political economy make it impossible to determine a priori how much cropland will ultimately be part of forest landscape restoration efforts. Therefore, two scenarios alternative to a BAU scenario were generated to provide a lower and upper bound of the impact that restoration on cropland area would have on food security.

The BAU scenario makes assumptions regarding GDP, population, and agricultural productivity growth without adoption of climate-smart practices (see Robinson et al. [2015] for details on these assumptions). All scenarios assume that agriculture is developing under climate change conditions. Simulations in the DSSAT and IMPACT models use climate change scenarios derived from the work of the Intergovernmental Panel on Climate Change *Fifth Assessment Report* (IPCC AR5). Climate change projections are generated through two global circulation models—GFDL-ESM2M (Dunne et al. 2012) and HadGEM2-ES (Jones et al. 2011)—under a Representative Concentration Pathway of 8.5 (Meinshausen et al. 2011). The GFDL climate change scenario can be considered as drier and cooler than that of the HadGEM. In addition, IMPACT's economic model uses trends in population and income growth obtained using the Shared Socioeconomic Pathway 2, a middle-of-the-road projection developed for the IPCC AR5 (O'Neill et al. 2014). The BAU scenario reflects the use of current practices and technologies throughout the simulated period of 2010–2030. This scenario includes information on representative cultivars, planting density, planting and harvesting dates, tillage practice, irrigation schemes, and residue harvest rates.

The alternatives to the BAU scenario are constructed by assuming that farmers who are currently using a particular set of practices to produce either maize, wheat, or rice are offered a portfolio of alternatives from which to choose. Farmers choose among this portfolio of practices the alternative that returns the higher yield gain as compared with BAU. If none of the alternatives increases yields, farmers retain the current practices. Yields are compared at the end of the first year after which if an alternative practice is deemed superior it is assumed to be adopted for the remaining of the period considered. Changes in agricultural commodity prices, production, soil organic carbon and greenhouse gas (GHG) emissions are computed annually.

The first alternative scenario (lower-bound scenario) minimizes the amount of agricultural land involved in forest landscape restoration efforts. It is constructed by selecting from the area identified as degraded by Bao, Nkonya, and Mirzabaev (2016) area that contains agricultural activities. Each area unit (pixel) is characterized by the ratio of agricultural land by degraded area—the lower the ratio, the smaller the amount of agricultural land in an area targeted for forest landscape restoration. The pixels are then ordered in ascending order and chosen according to their agriculture–by–degraded land value to provide enough restorable degraded land to meet the Bonn Challenge. Areas that are too remote and that do not have recorded agricultural activities are not considered to be candidates for the forest landscape restoration approach. This scenario also internalizes the potential limits in the uptake of restoration practices. In a recent study, Rosegrant et al. (2014) identified adoption ceilings for a wide variety of agricultural management practices and technologies. Even for widely accepted practices, they found adoption limits in the order of 40–60 percent. The rate of adoption of restoration practices in areas targeted by forest landscape restoration activities is important—the lower the uptake, the greater the area that must be targeted by programs. For the lower-bound scenario, we use the average of the adoption ceilings identified by Rosegrant et al. (2014) and assume that restoration actually occurs only on 50 percent of the area targeted. In essence, this means that in order to have 350 million hectares that implement forest landscape restoration practices, 700 million hectares would have to be targeted by restoration projects.

The second scenario alternative to the BAU, the upper-bound scenario, assumes that forest landscape restoration efforts can take place on any of the degraded area identified by Bao, Nkonya, and Mirzabaev (2016) that contains agriculture and that is adopted on 100 percent of the area targeted for restoration. To assess the maximum benefits from implementing restoration practices on cropland, among all pixels classified as degraded in Bao, Nkonya, and Mirzabaev (2016), we selected the 350 million hectares in which the restoration practices considered would return the highest gross revenue gains.

None of the scenarios considered accounts for changes in production costs due to the adoption of alternative practices. This is mostly because there is no sufficiently spatially disaggregated information on costs that can be included in the analysis. When increased production costs cause the profitability of an alternative to the BAU to be lower than those of the BAU, the alternative is not adopted even when yields are higher. Therefore, when one assumes that an alternative is adopted when yields are higher than using current practices and ignores production costs one tends to overestimate adoption. The first scenario, the lower-bound scenario, heuristically includes the effects of production costs by assuming adoption rate of 50 percent.

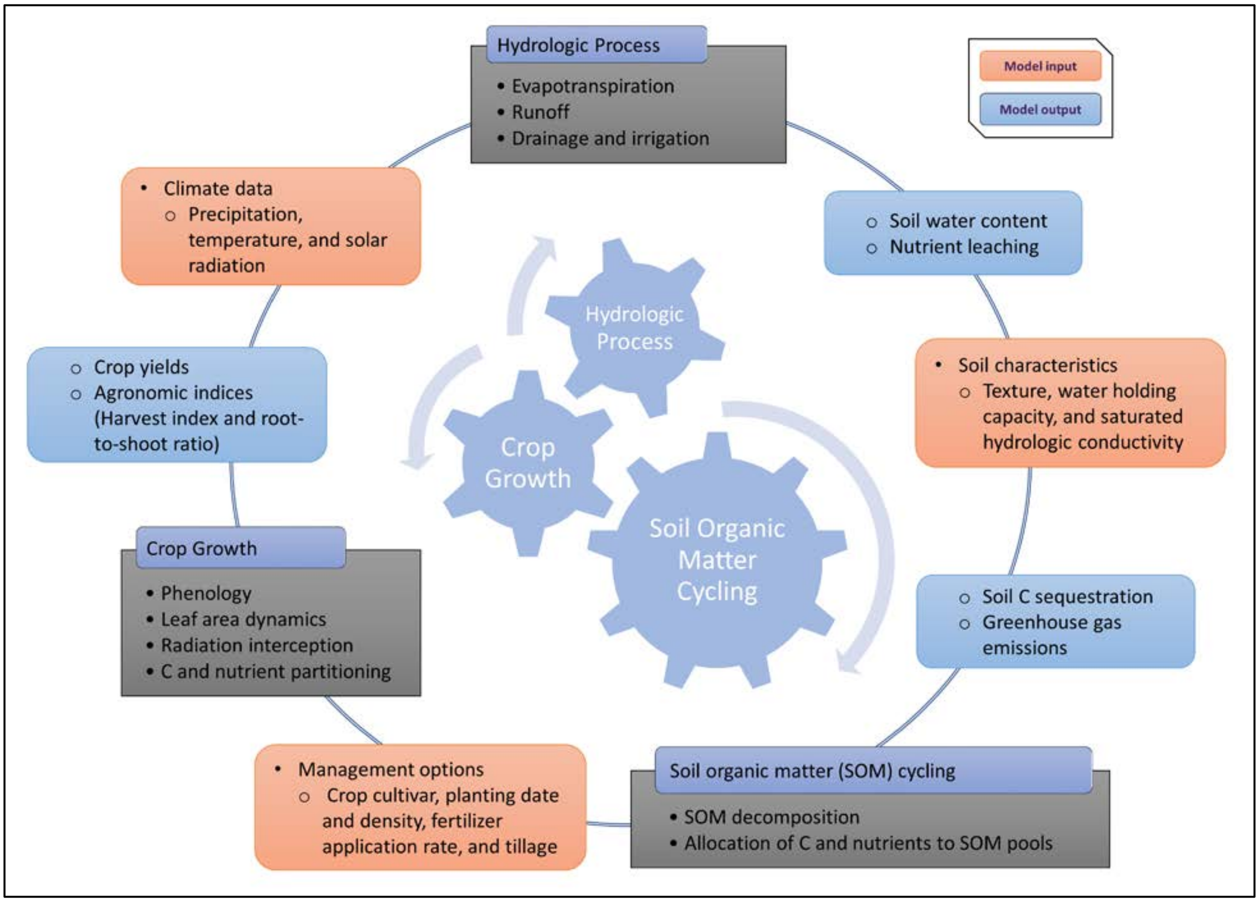
The second alternative scenario (upper-bound scenario) assumes a 100 percent adoption rate therefore overestimating adoption. The results of this scenario should be interpreted as the highest possible effects of adopting conservation practices on degraded cropland[4].

Crop Production

The ex ante assessment of production under different scenarios (BAU and alternatives) is based on the use of DSSAT (Jones et al. 2003). DSSAT integrates the effects of biophysical elements of the crop systems (interaction among soil, weather, and crop) and management options (type of tillage, nutrient application, and water availability) to simulate production outcomes originating from interactions among the components of the cropping system. Crop growth and yields are driven by spatially explicit climate scenarios, soil properties, and management practice, which are simulated globally at spatial disaggregation of 0.5 degrees. Figure 4.2 provides a summary of the data needed by DSSAT and the model output.

[4] It is possible the alternative practices are adopted when they decrease yields compared to the BAU if production costs are reduced more than proportionally. We ignore this possibility given that it is difficult to imagine that countries would favor the widespread use of technologies that reduce yields given the pressure of population growth and changing diets.

Figure 4.2 DSSAT input, output, and data flow



Source: Authors
Note: C = carbon.

Agricultural Practices and Technologies That Can Increase Yields While Restoring Soil Fertility

Our analysis focuses on crop production and, in particular, on the crops that are most frequently present in degraded areas: maize (*Zea mays*), wheat (*Triticum aestivum*), and rice (*Oryza sativa*) (see Table 4.1). Maize, wheat, and rice also represent about 41 percent of the global harvested area and are important staple crops across the globe. They also represent approximately 64 percent of greenhouse gas emissions generated by crop production globally (Carlson et al. 2016).

For these crops, we consider a set of agricultural practices that are thought to have the potential to be adopted widely and are already utilized and tested in some areas. The practices are known to restore soil fertility and lead to sustainable production under changing climate regimes and are therefore good complements to the forest landscape restoration approach. These practices are also part of a new proposed approach to agriculture called climate-smart agriculture (CSA). The Food and Agriculture Organization of the United Nations (FAO) introduced the concept of CSA in 2009 (FAO 2009). CSA proposes a type of agricultural development expected to deliver on multiple outcomes: increase sustainable production and increase resilience to climate shocks and extreme weather events while reducing emissions or at least emissions per unit of output (emission intensity).

A review of the literature—and of the FAO *CSA Sourcebook* in particular (FAO 2013)—reveals that there is a general consensus around the suitability of some specific practices for this approach. Three technologies are identified as having a high potential for large-scale adoption, and most of these have already been used or tested in some regions. The technologies considered for maize and wheat are no tillage, integrated soil fertility management, and nitrogen-use efficiency for rice (see Table 4.2).

Table 4.2 Climate-smart technologies considered for this study.

CSA technology	Definition	Crop	Reference
No tillage	Minimum or no soil disturbance, in combination with residue retention, crop rotation, and use of cover crops	Maize, wheat	Erenstein et al. 2008, 2012; Hobbs, Sayre, and Gupta 2008; Pittelkow et al. 2015b; Powlson et al. 2014
Integrated soil fertility management	Combination of chemical fertilizers, crop residues, and manure/compost	Maize, wheat	Agegnehu, vanBeek, and Bird 2014; Chivenge, Vanlauwe, and Six 2011; Vanlauwe et al. 2011; Gentile et al. 2008
Nitrogen-use efficiency	Strategic placement of urea near the root zones of crop plants	Rice	Bandaogo et al. 2015; Huda et al. 2016; Gaihre et al. 2015

Source: Authors' compilation.

The existing literature on conservation agriculture in which no-till is an essential component points to an increase in yields. However, the effects are variable, as they depend on a range of location-specific exogenous—for example, climate and learning processes—and endogenous conditions—for example, soil type (Erenstein et al. 2012; Lal 2015; Pittelkow et al. 2015a). In some conditions, short-term productivity may even decrease under conservation agriculture (Pittelkow et al. 2015a), while yields are more stable and often increase with time, especially under dry or drought-stressed conditions (Corbeels et al. 2014; Pittelkow et al. 2015a).

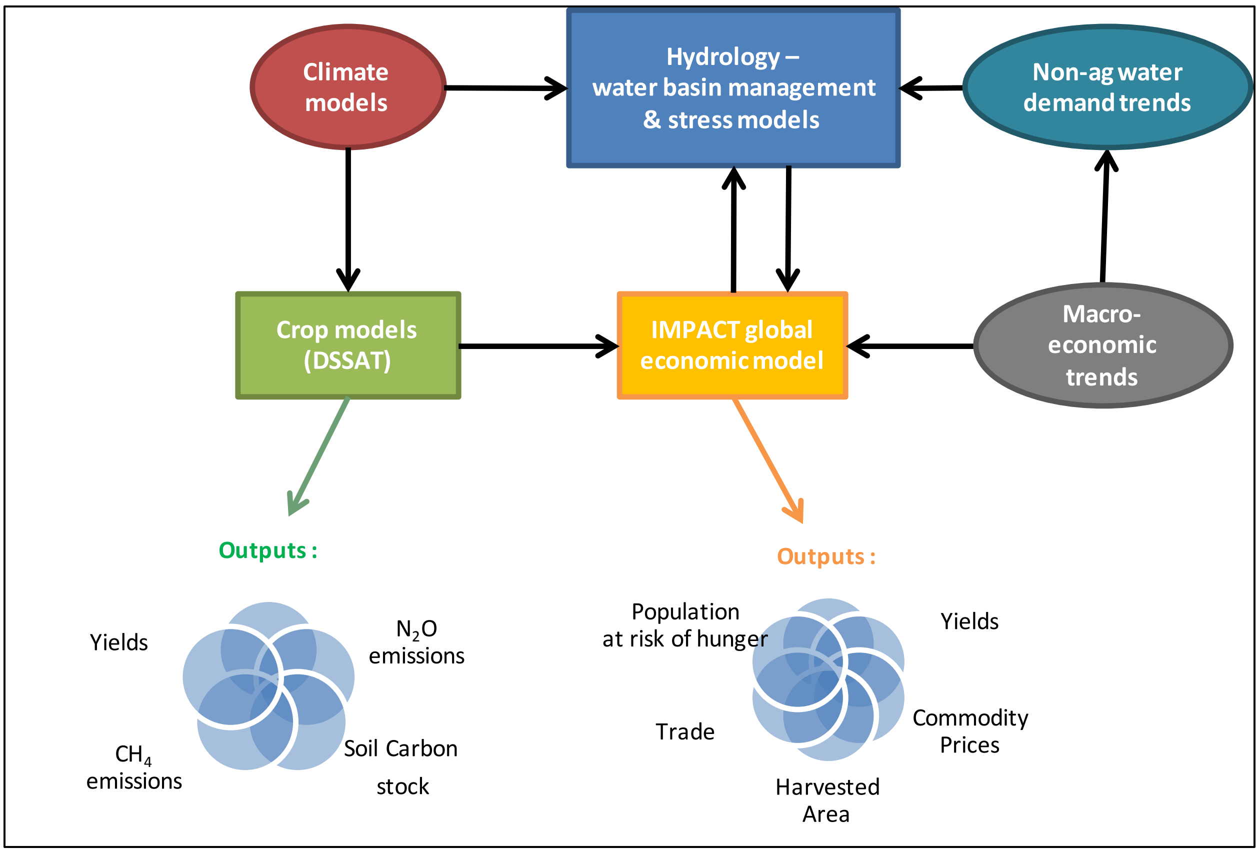
Integrated soil fertility management (ISFM) is a set of locally adapted practices that use residues with both synthetic fertilizers and organic inputs (for example, animal manure and/or green manure). The aim is to increase productivity through the efficient use of nutrients (Vanlauwe et al. 2011). ISFM is built upon the combined use of mineral fertilizers and locally available soil amendments (such as lime and phosphate rock) and organic matter (crop residues, compost, and green manure) to replenish lost soil nutrients. It has been recognized that ISFM contributes to improvements in the resilience of soils and agricultural production to weather variability.

Nitrogen-use efficiency is an approach that aims to reduce the use of nitrogen and provide it to the plant root system more efficiently. There are various methods of application; in general, they are key to both increased production and reduced emissions (FAO 2013). Broadcast application of nitrogen in rice fields leads to 60–70 percent nitrogen losses, which directly contributes both to water pollution and greenhouse gas emissions. The placement of urea "supergranules" deep in the soil, however, provides a slow release of fertilizer near the root system of rice plants, improving the efficiency of nutrient uptake and limiting nitrogen losses.

Market and Food Security Effects of Restoration on Crop Production

The effects of restoration efforts on crop production are evaluated using the agricultural trade model IMPACT (Islam et al. 2016; Robinson et al. 2015; Rosegrant et al. 2014). IMPACT, which is actually a suit of models working together (see Figure 4.3), is a partial equilibrium multimarket model of the agriculture sector that models the behavior of a global competitive agricultural market and simulates supply, demand, and prices for agricultural commodities at the country level. IMPACT has a broad record of applications, ranging from assessing the potential effects of climate change on global food production and nutrition (Springmann et al. 2016) to evaluating the global effects of biofuel production (Rosegrant 2008) to country-level assessments of low-emission development strategies (De Pinto et al. 2016). The crop yields with current and alternative practices obtained from DSSAT are used as input for the simulations implemented in the IMPACT model. The IMPACT model returns areas allocated to crops to satisfy demand for agricultural products, commodity prices, and estimates of the number of malnourished children and people at risk of hunger.

Figure 4.3 IMPACT, connectivity, and information flow



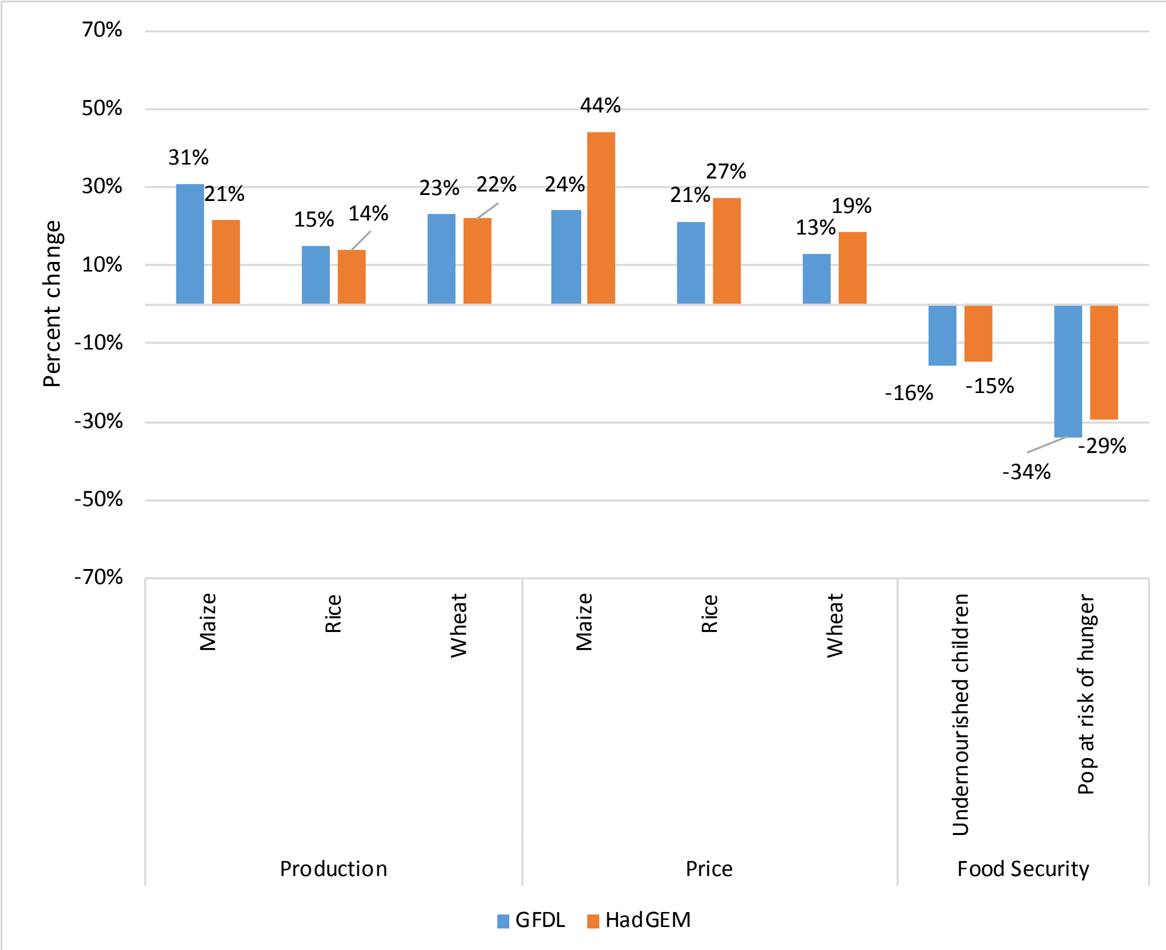
Source: Modified from Robinson et al. 2015.
Notes: N_2O = nitrous oxide; CH_4 = methane.

5. RESULTS

Business-as-Usual Scenario

The BAU scenario, which uses IMPACT projections for 2010–2030 (Figure 5.1), indicates that production of the main cereals of maize, rice, and wheat is expected to increase by 21–31 percent, 14–15 percent, and 22–23 percent, respectively, depending on the particular climate scenario used. Despite production growth, which should drive prices down, population and economic growth, which both effect people's diets, will also affect commodity prices. Prices of maize, rice, and wheat are projected to increase by 24–44 percent, 21–27 percent, and 13–19 percent, respectively. The price of maize, in particular, is affected by an increased demand for animal proteins and the use of this crop as feed for livestock. These changes, together with rising incomes, affect not only the overall availability and accessibility of food for millions of people but also their general hunger and nutritional status. In 2030, the number of undernourished children is projected to decrease by 15–16 percent, and the population at risk of hunger is projected to decrease by 29–34 percent, compared to 2010.

Figure 5.1 BAU scenario: 2010–2030—Changes in production, prices, undernourished children, and population at risk of hunger



Source: Authors.

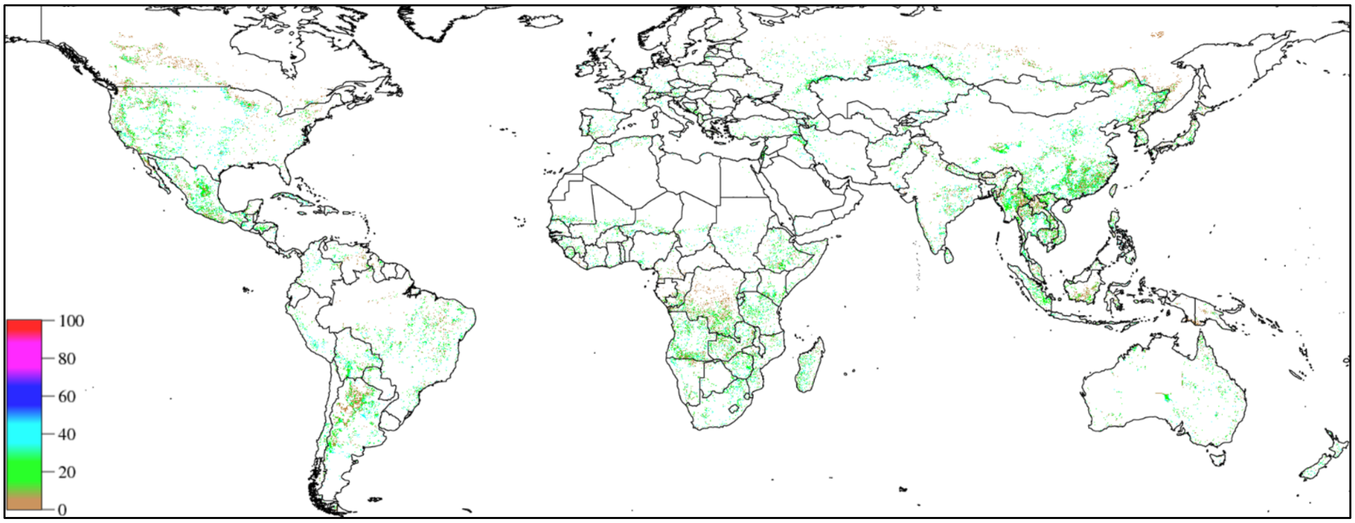
Forest Landscape Restoration with Minimum Involvement of Agriculture (Lower-Bound Scenario)

This scenario represents an implementation of the forest landscape restoration approach that includes (and attempts to minimize) the amount of agricultural area involved in restoration. It assumes that restoration practices will be adopted only on 50 percent of the area targeted.

Results indicate that 63.0 million hectares of cropland (approximately 5 percent of global harvested area) and 97.1 million hectares of pastureland would be present in areas targeted for restoration. The total amount of forest present in this area is 196.8 million hectares (7.2 percent of global forests), 93 million hectares of which is classified as tropical forest (7.1 percent of global tropical forests). Figure 5.2

displays the location of cropland present in areas targeted for restoration. The legend reports the ratio of cropland area by SPAM grid cell. Although cropland involvement in restoration is spread globally, Africa south of the Sahara, Southeast Asia, and North and South America are the regions with the greatest amounts of restorable cropland area.

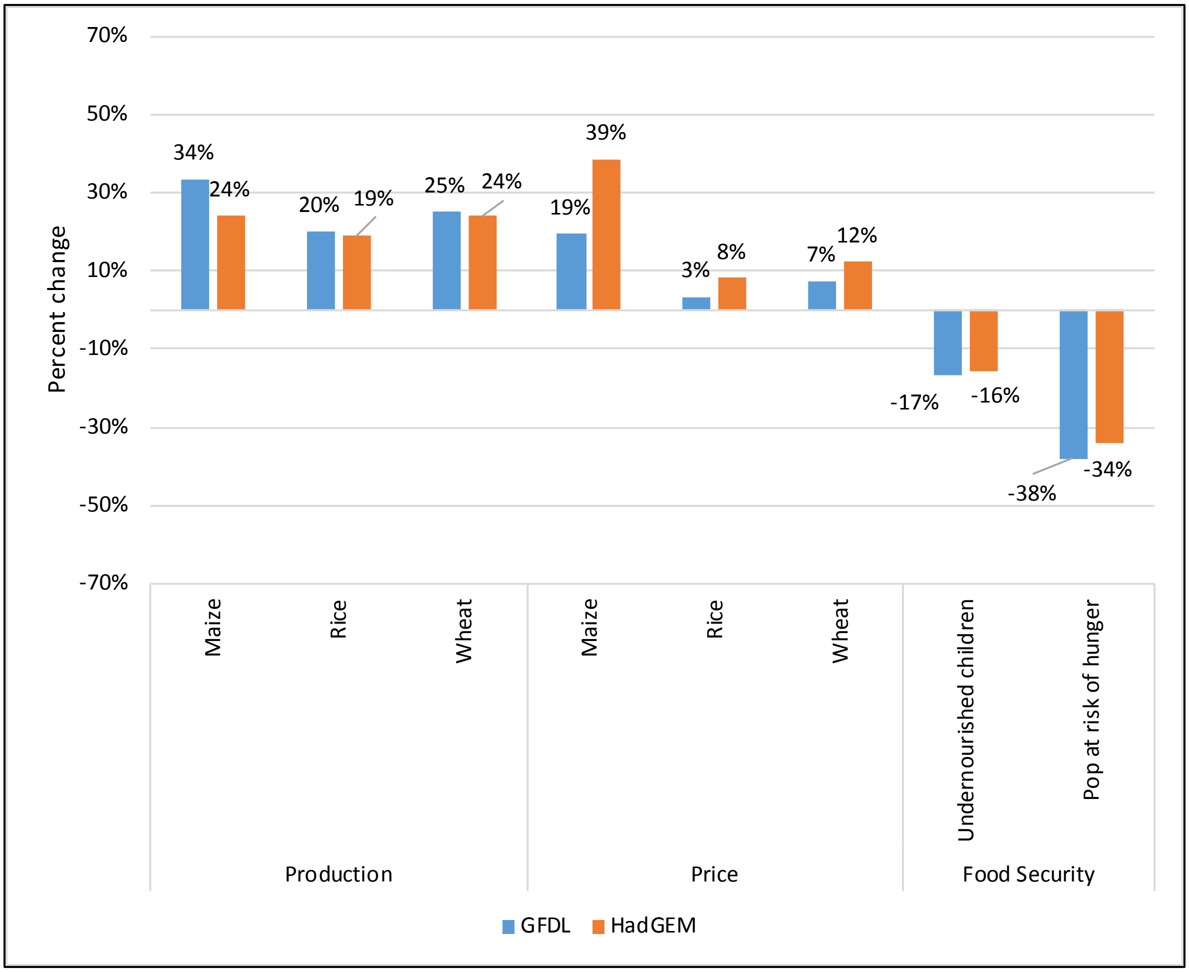
Figure 5.2 Lower-bound scenario—Location and density of cropland in areas targeted by restoration efforts



Source: Authors.

Simulations indicate that the adoption of the alternative practice considered in this study would have an appreciable effect on production, prices, and food security (Figure 5.3). According to these simulations, production increases more than projected by the BAU scenario (about 3 percent for maize, 5 percent for rice, and 2 percent for wheat). Commodity prices are still projected to increase, though they are less than the projections in the BAU scenario (5 percent less for maize, 18–19 percent less for rice, and 6–7 percent less for wheat). The compounded effect of higher production and lower prices increases the availability and accessibility of these food staples, with a consequent projected reduction in the number of undernourished children and the population at risk of hunger as compared with BAU. The number of undernourished children is reduced by an additional 1 percent (3,000,000 children) and the population at risk of hunger by an additional 4–5 percent (70,000,000–77,000,000 people).

Figure 5.3 Lower-bound scenario: 2010–2030—Changes in production, prices, undernourished children, and population at risk of hunger



Source: Authors.

Other important positive benefits also result from these changes. First of all, the combination of higher production and lower prices reduces producers' incentives to expand production areas for wheat and rice. Their harvested area is projected to decrease by 0.8 percent for wheat and 2.5 percent for rice. Area allocated to maize is projected to increase by approximately 0.3%, which is likely due to the increase in the demand for food for livestock. Despite this increase, when the three crops are considered together, total harvested area is projected to decrease. However, the effects on harvested area are significantly different from one region of the world to the other (see Figure A.2 in the appendix). Although the reduced demand for harvested area could potentially reduce the encroachment of cropland into environmentally sensitive and carbon-rich areas like forests, additional research is necessary to evaluate the specific regional changes vis-à-vis the presence of environmentally sensitive areas. In addition, soil organic carbon concentration, which increases not only fertility but also soil water retention, is estimated to grow by approximately 0.4 Mg ha^{-1} yr^{-1} over the area that adopts the alternative practices; due to the increases in the efficiency of production, greenhouse gas emissions are expected to be reduced by 0.3 Mg CO_2 e ha^{-1} yr^{-1}.

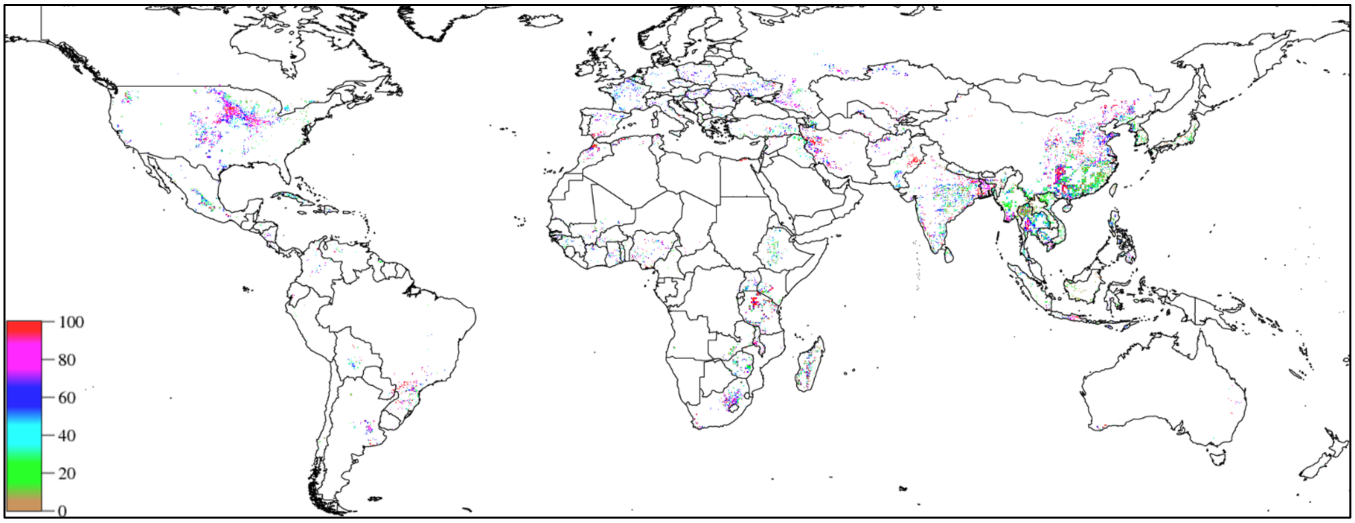
Forest Landscape Restoration Efforts with Maximum Involvement of Agricultural Land (Upper-Bound Scenario)

The upper-bound scenario explores the effects of restoration efforts on cropland identified with the objective of maximizing the benefits of including crop production in restoration areas. It assumes that restoration practices will be adopted in all of the area targeted for restoration.

Results indicate that 148 million hectares of cropland (approximately 12 percent of global harvested area) and 79 million hectares of pastures would be present in areas targeted for restoration. About 70 million hectares of forest (about 2.6 percent of all forests) would also be present in this area; 31 million hectares of the forest are classified as tropical forest (roughly 2.4 percent of global tropical forests).[5] Figure 5.4 shows the location of cropland involved in restoration efforts for this scenario. These results provide an indication of where restoration efforts would return the highest benefit in terms of gross revenues. It should be noted how, in this scenario, restoration on cropland concentrates in areas different from in the previous scenario (Figure 5.2), such as the American Midwest, Iran, Bangladesh, and Indonesia. Some locations are common to both scenarios (Kenya, Zambia, Tanzania, Zimbabwe, Madagascar, China, and Thailand, to name a few).

[5] Because the adoption rate of restoration practices is assumed to be 100 percent, the total area targeted for restoration must sum to 350 million hectares to satisfy the Bonn Challenge. The area not reported in the text is allocated to other land use categories, such as grassland, savanna, and so on.

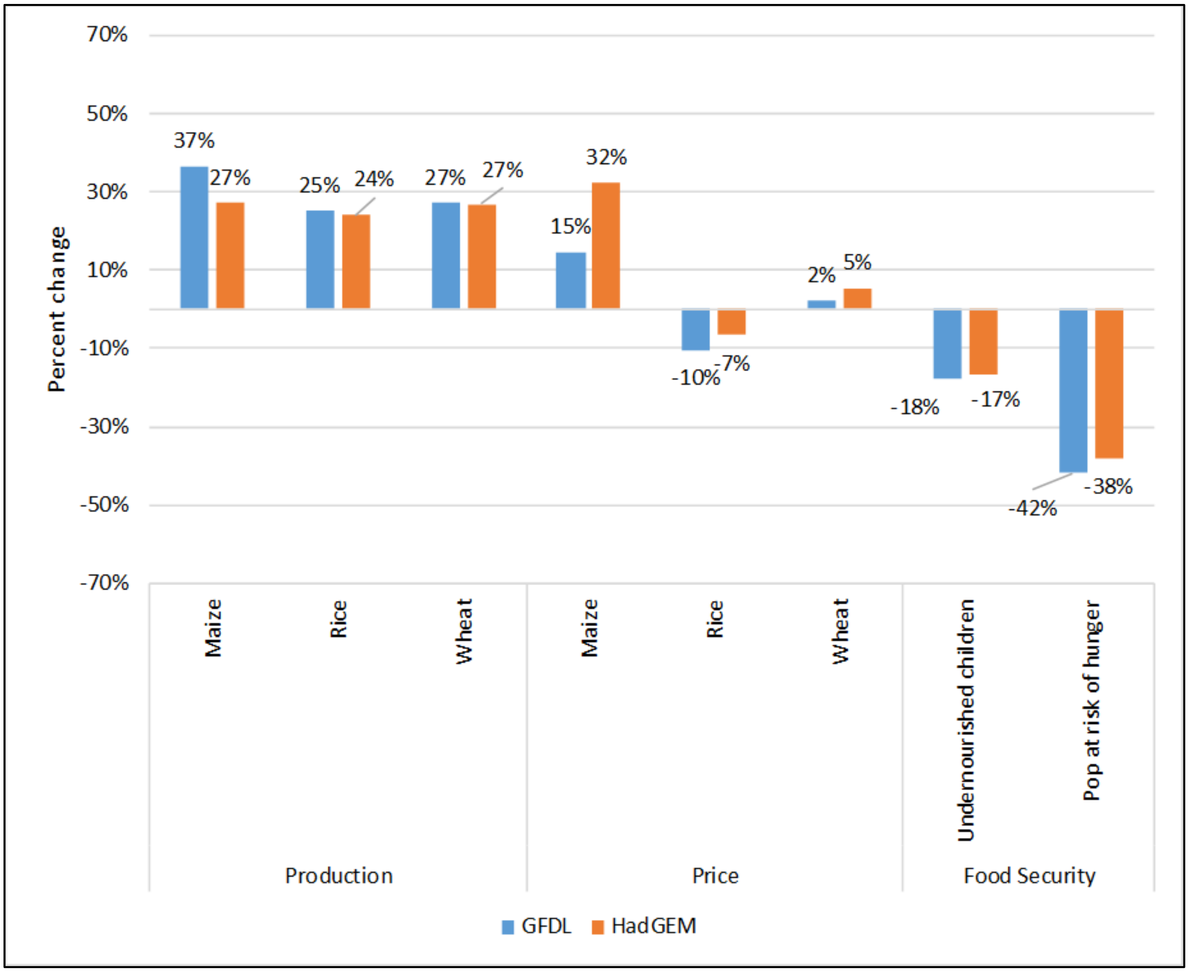
Figure 5.4 Upper-bound scenario—Location and density of cropland in areas targeted by restoration efforts



Source: Authors.

As expected, simulation results indicate that a wider uptake of conservation practices on degraded land would have an even greater effect on production and prices (Figure 5.5). Production increases by about 6 percent for maize, 10 percent for rice, and 3–4 percent for wheat compared to the BAU scenario; prices increase less than what is projected in the BAU scenario—9–12 percent less for maize, 31–34 percent less for rice, and 11–14 percent less for wheat. The combined effect of higher production and lower prices increases the availability and accessibility of maize, rice, and wheat, with a consequent reduction in the number of undernourished children and in the population at risk of hunger as compared with BAU. The number of undernourished children is reduced by an additional 2 percent (6,000,000 children) and the population at risk of hunger by an additional 8–9 percent (134,000,000–151,000,000 people).

Figure 5.5 Upper-bound scenario: 2010–2030—Changes in production, prices, undernourished children, and population at risk of hunger



Source: Authors.

Even for this scenario, important co-benefits are generated by increased production. Similar to the lower-bound scenario, the incentives to expand production area for wheat and rice are reduced, with their harvested area projected to decrease by about 1.5 percent, and 5 percent, respectively. Area allocated to maize is projected to increase between 0.5 percent and 0.9 percent due to the increase in the demand for livestock feed. Considered all together, total harvested area is projected to decrease. However, these effects on harvested area are different from one region of the world to another (see Figure A.4 in the appendix). Soil organic carbon concentration is estimated to grow by approximately 0.4 Mg ha^{-1} yr^{-1}, and greenhouse gas emissions are expected to be reduced by 0.2 Mg CO_2 e ha^{-1} yr^{-1}.

6. LIMITS OF THIS STUDY AND FUTURE EXTENSIONS

At this stage, the analysis focuses on crop production, acknowledging that it is only a first approximation of the gains that could be obtained by undertaking restoration activities on all different types of agricultural land. This focus is due to current modeling capabilities, which prevent the representation of agroforestry, silvopastoral, and agrosilvopastoral systems at the global level with the same level of accuracy of crop production (Luedeling et al. 2014, 2016). Therefore, the role of agroforestry on a global scale remains important but unexplored. Agroforestry is promoted as a way of reconciling multiple objectives within a single farming system, such as enhancing soil organic matter, erosion control, and improved nutrient cycling, all of which increase crop productivity and drought tolerance. However, it is important to recognize that agroforestry can work well in some but not all contexts; although agroforestry can be an attractive option for smallholder farmers, it can be in conflict with large-scale, mechanized farming, particularly when fossil fuels are inexpensive and labor is expensive. Even though the list of successful experiences with agroforestry is growing, they are still localized and difficult to upscale.

Although we cannot perform a global assessment, some of the regional benefits generated by agroforestry systems can be evaluated with some ad hoc analysis. Agroforestry systems include a long list of land management practices, such as boundary plantings, hedgerow intercropping, live fences, improved fallows, and mixed-strata agroforestry. Some of these systems—for example, parklands—are relatively well established in some regions of Africa. Parklands occur in various latitudes, and while the most well-known parklands are located in semiarid or subhumid zones (Bourlière and Hadley 1983), systems with scattered trees in fields with similar purpose are also widespread in southern Africa (Campbell, Clarke, and Gumbo 1991; Maghembe and Seyani 1991). Extensive intercropping systems under widely spaced multipurpose trees, as is typical of parkland systems, are considered to deliver benefits of limited magnitude (Nair 2012); however, if such systems were used in combination with conservation practices in crop production, the compounded effects would be significant. A tree species that is spread in parklands, widely grown by farmers in association with cereals, and receiving increasing attention by researchers is

Faidherbia albida. This leguminous nitrogen-fixing tree indigenous all over Africa has a unique compatibility with cropping systems due to its "reverse foliation"—that is, it sheds its leaves during the wet season, thus eliminating the competition for sunlight with the crops that grow under it. Furthermore, the leaves that grow during the dry season are high in nitrogen and can function as nitrogen fertilizer.

The upper-bound scenario simulated in this study shows the degraded area in eastern and southern Africa, where conservation practices should replace current crop production practices (see Figure 5.4 for South Africa, Zimbabwe, Zambia, Uganda, Tanzania, Madagascar, Malawi, Kenya, and Ethiopia). This area totals approximately 4.5 million hectares, and simulations indicate that the average annual gains in yield are of some importance (1.3 Mg ha^{-1} yr^{-1} for maize, 0.4 Mg ha^{-1} yr^{-1} for wheat, and 1.1 Mg ha^{-1} yr^{-1} for rice). However, adopting cropland restoration practices on this land does not appear to reduce greenhouse gas emissions by significant amounts, mostly due to the local soil and weather conditions. Over the area, the estimated annual reduction of greenhouse emissions is approximately 1.4 million Mg CO_2 e ha^{-1} yr^{-1}, or about 0.3 Mg CO_2 e ha^{-1} yr^{-1}.6 Introducing an extensive intercropping system, together with conservation practices in crop production, would substantially increase the climate change mitigation benefits. Mbow et al. (2014) reported a carbon sequestration potential for parkland agroforestry systems with *Faidherbia albida* to be in the range of 0.2–0.8 Mg C ha^{-1} yr^{-1}. Using the authors' suggested average value of 0.5 Mg C ha^{-1} yr^{-1}, we can calculate that the contribution of this system to mitigation would be about 8.3 million Mg CO_2 e ha^{-1} yr^{-1}, which is approximately six times the greenhouse gas reduction obtained using only agricultural practices.7 Therefore, the combination of agroforestry and alternative crop production practices promotes greater food production, increased revenues, reduced pressure for cropland expansion, healthier soils, and increased carbon sequestration.8

[6] Soil organic carbon is estimated to increase by 0.15 Mg C ha^{-1} yr^{-1}, but greenhouse gas emissions are expected to be reduced by 0.3 Mg CO_2 e ha^{-1} yr^{-1}.

[7] 1.00 Mg of carbon equals 3.67 Mg of CO_2.

[8] It is also documented that in some areas and conditions, nitrogen-fixing trees on crop fields offer yield increases between 50 and 300 percent in associated cereal crops (Sileshi et al 2008); that they also promote restoration by replenishing the soil stock of organic carbon (Nair 2012).

Similarly important but left to future research is the role of livestock and pastureland as components of silvopasture and agrosilvopasture systems. A relatively extensive literature demonstrates how silvopastoral systems can increase productivity, sequester significant amounts of carbon, and increase soil organic carbon (Dulormne et al. 2003; Udawatta and Jose 2011; Mosquera-Losada, Freese, and Rigueiro-Rodríguez 2011). However, existing models cannot capture the complexity and diversity of these systems due to the wide range of climatic and environmental settings. Given the important benefits expected to accrue from agroforestry and silvopasture and agrosilvopasture systems, additional work on identifying locally viable options and scalable innovations, as well as on the models that accurately represent these systems, is of paramount importance.

7. CONCLUSION

Productive land and fertile soils are essential to food production and human existence; thus, their degradation poses significant challenges for the well-being of all people around the world. Furthermore, land provides a wide range of other essential ecosystem services, including carbon sequestration, which could contribute to limiting global warming. Land and soil degradation poses a substantial challenge to meeting global food needs, and it generates significant risks to people, particularly in rural and poor countries that are heavily dependent on natural resources. Given its magnitude, the problem of degradation must be addressed globally; as such, the international community is currently engaged in several initiatives to address degradation globally. The most recent is the Bonn Challenge and its extensions, which aim to bring 150 million hectares of the world's deforested and degraded land into restoration by 2020 and 350 million hectares by 2030.

Underlying the Bonn Challenge is the forest landscape restoration approach, which aims to restore the ecological integrity of landscapes while improving human well-being through multifunctional landscapes. The forest landscape restoration approach can involve the restoration of large tracts of degraded or fragmented forestland; in addition, a significant amount of restoration opportunities are thought to be on or adjacent to degraded agricultural or pastoral land. The role of agricultural land in the proposed approach is key to promoting a wide uptake of restoration efforts. The presence of agriculture in restoration areas is expected to promote the active role of communities and a broad implementation of restoration plans. However, well-documented barriers exist that prevent farmers from widely adopting beneficial practices. The forest landscape restoration approach operates at the nexus of these competing forces.

This paper provides insights into the extent of the involvement of degraded cropland in landscape restoration efforts at a global scale. It also assesses the benefits of such involvement on several dimensions, including food security. The benefits are generated by the multiple gains that derive from adopting a series of alternatives to current crop production practices. Among these benefits are increased production and lower prices, which increase access to food staples and lead to a substantial reduction in the number of undernourished children and people at risk of hunger (from 3,000,000–6,000,000 fewer undernourished children and from 70,000,000–151,000,000 fewer people at risk of hunger). Furthermore, the results indicate that increased productivity reduces the demand for cropland and potentially reduces the pressure for expanding cropland into environmentally sensitive areas. Simulations also indicate that it is possible to use agricultural practices and technologies that improve soil fertility and reduce greenhouse gas emissions, while also increasing yields and productivity. The benefits—not only to farmers but also to the broader population—generated by restoration practices on crop production strongly suggest that a forest landscape restoration approach that meaningfully integrates agriculture can facilitate the implementation of restoration plans on large amounts of land. The fact that current modeling capabilities prevent us from including the use of agroforestry or agrosilvopastoral systems in the simulated scenarios indicates that our results are likely to be an underestimation of the full benefits of restoration practices on agricultural land. For example, a judicious use of agroforestry can provide an additional source of vitamins and micronutrients, with important effects on the nutritional qualities of farm output.

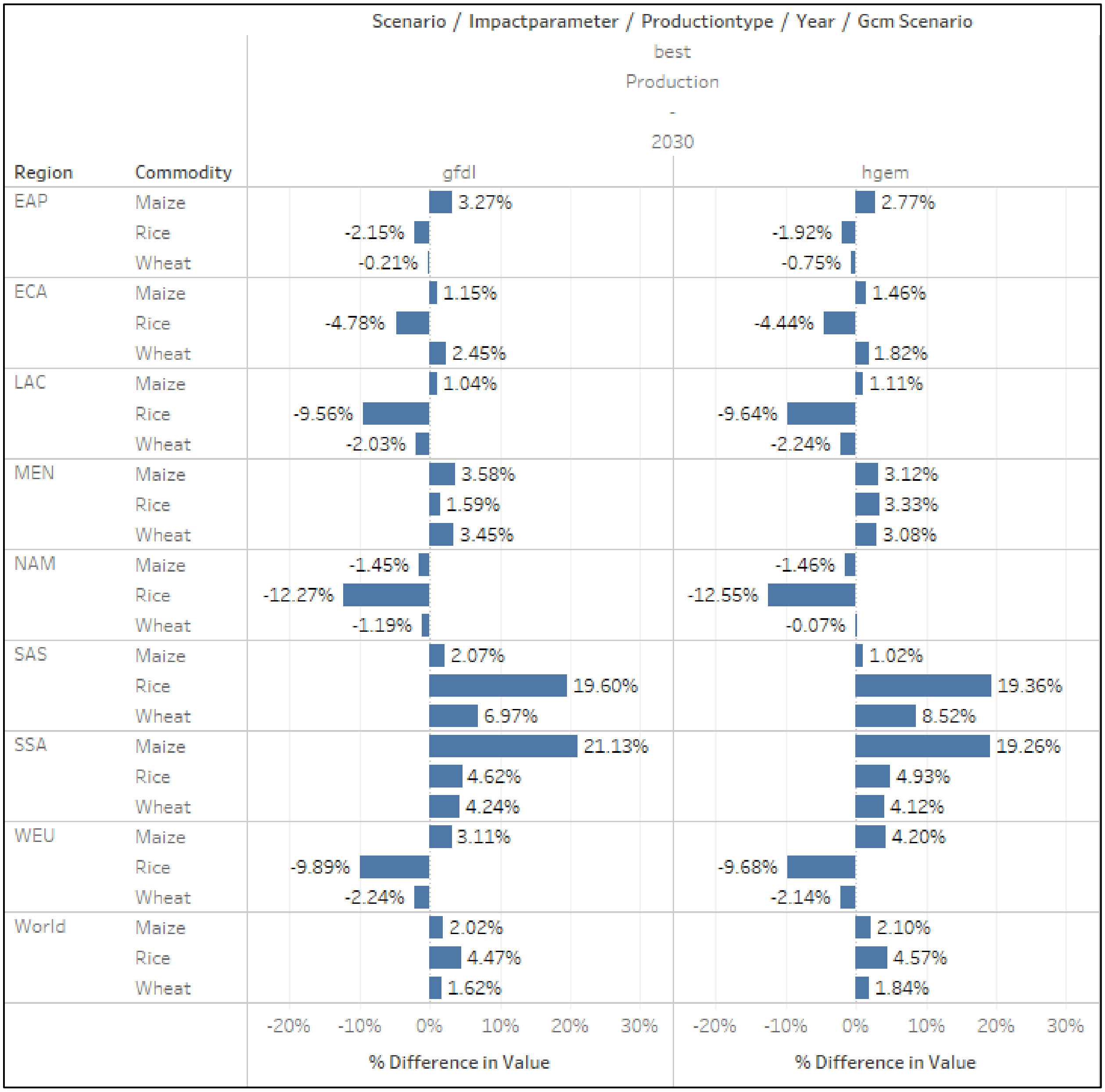
Building on our simulations, we show the additional benefits that can be harnessed by combining agroforestry with the adoption of conservation practices in crop production. Research consistently shows that areas with 50 percent tree cover on farms are associated with better nutrition and dietary diversity (Ickowitz et al. 2014).

Clearly, reducing global hunger and increasing food security are not only dependent on increasing production or yields. However, increasing agricultural production on degraded land often means intervening in regions (such as Africa south of the Sahara, India, and Southeast Asia; see Figure 5.2 and 5.4) where increasing farm output and incomes can make a substantial difference in the nutrition of poor households.

The results of this analysis not only confirm the findings of the many studies that have investigated the benefits of restoration in more localized settings but also should provide enough confidence to governments and policy makers that they can answer the many calls to invest in wide-scale restoration projects without jeopardizing their food security goals. Approaches that fully integrate agriculture in restoration projects, such as forest landscape restoration, not only can avoid trade-offs between restoration and food production but also can provide a framework to build on the synergies of multifunctional landscapes with significant benefits to food security. However, the overall positive outcomes are strongly dependent on how widely adopted conservation practices are, which points to the importance for policy makers to find and promote solutions to long-standing problems, such as the need for well-functioning extension services, proper amounts of good-quality information for farmers, and reliable and trustworthy institutions. Policies and instruments that allow for the proper accounting of social benefits and costs also must be in place to generate an equitable competition between the use of chemical inputs and alternative solutions to increasing land productivity such as agroforestry systems. Without addressing these barriers, farmers will continue to maximize their private short-term benefits, which might conflict with long-term societal goals. Finally, sufficient resources must be invested in studying the systems that work best given local specific geophysical, climate, and socioeconomic conditions and in developing the models that can facilitate the type of long-term planning horizon required for an adequate management of landscape restoration approaches.

APPENDIX

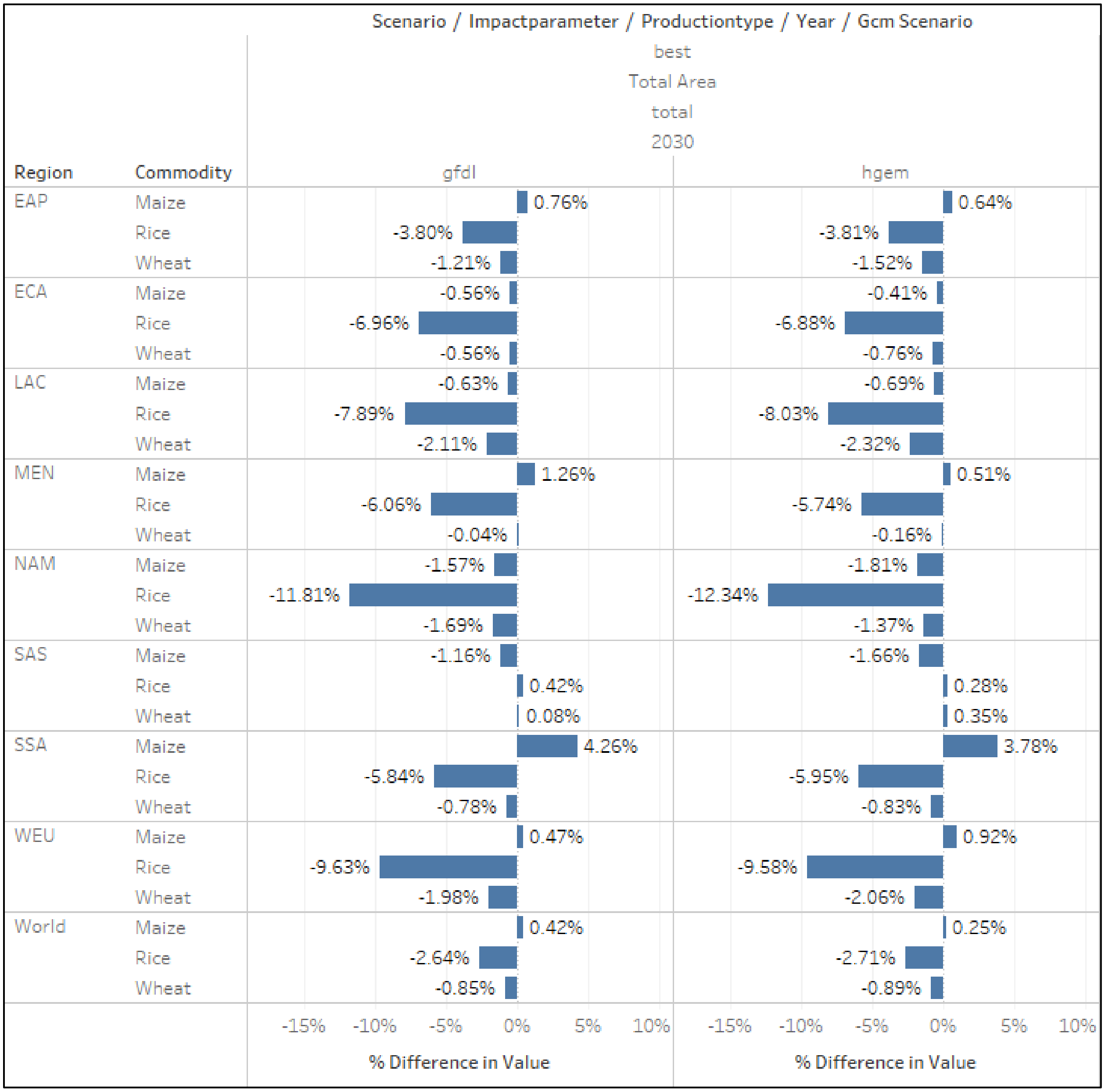
Figure A.1 Lower-bound scenario 2010–2030—Changes in production by commodity and region



Source: Authors.

Note: EAP = East Asia and Pacific; ECA = Eastern Europe and Central Asia; LAC = Latin America and Caribbean; MEN = Middle East and North Africa; NAM = North America; SAS = South Asia; SSA = Africa south of the Sahara; WEU = Western Europe.

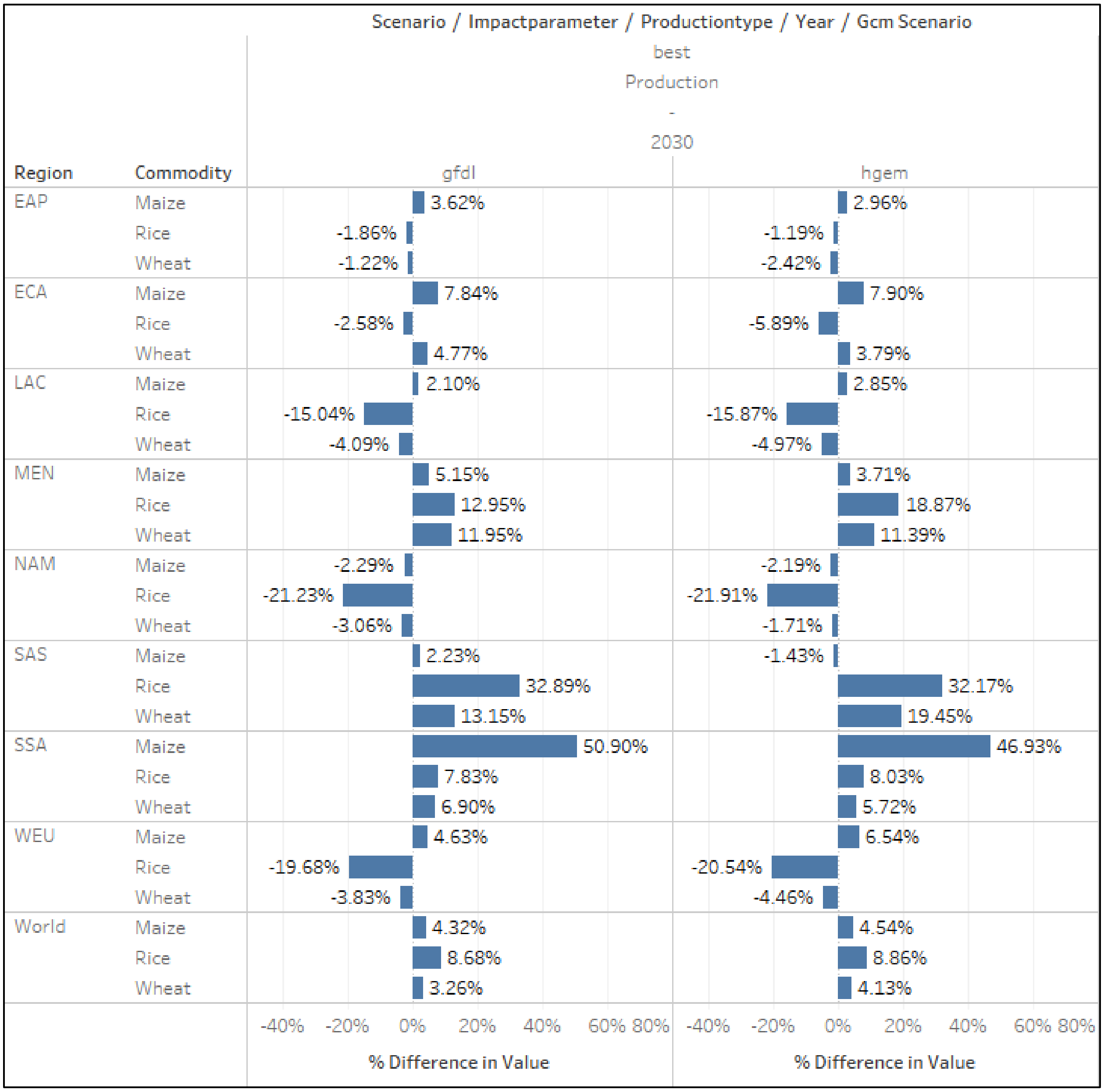
Figure A.2 Lower-bound scenario: 2010–2030—Changes in harvested area by commodity and regions



Source: Authors.

Note: EAP = East Asia and Pacific; ECA = Eastern Europe and Central Asia; LAC = Latin America and Caribbean; MEN = Middle East and North Africa; NAM = North America; SAS = South Asia; SSA = Africa south of the Sahara; WEU = Western Europe.

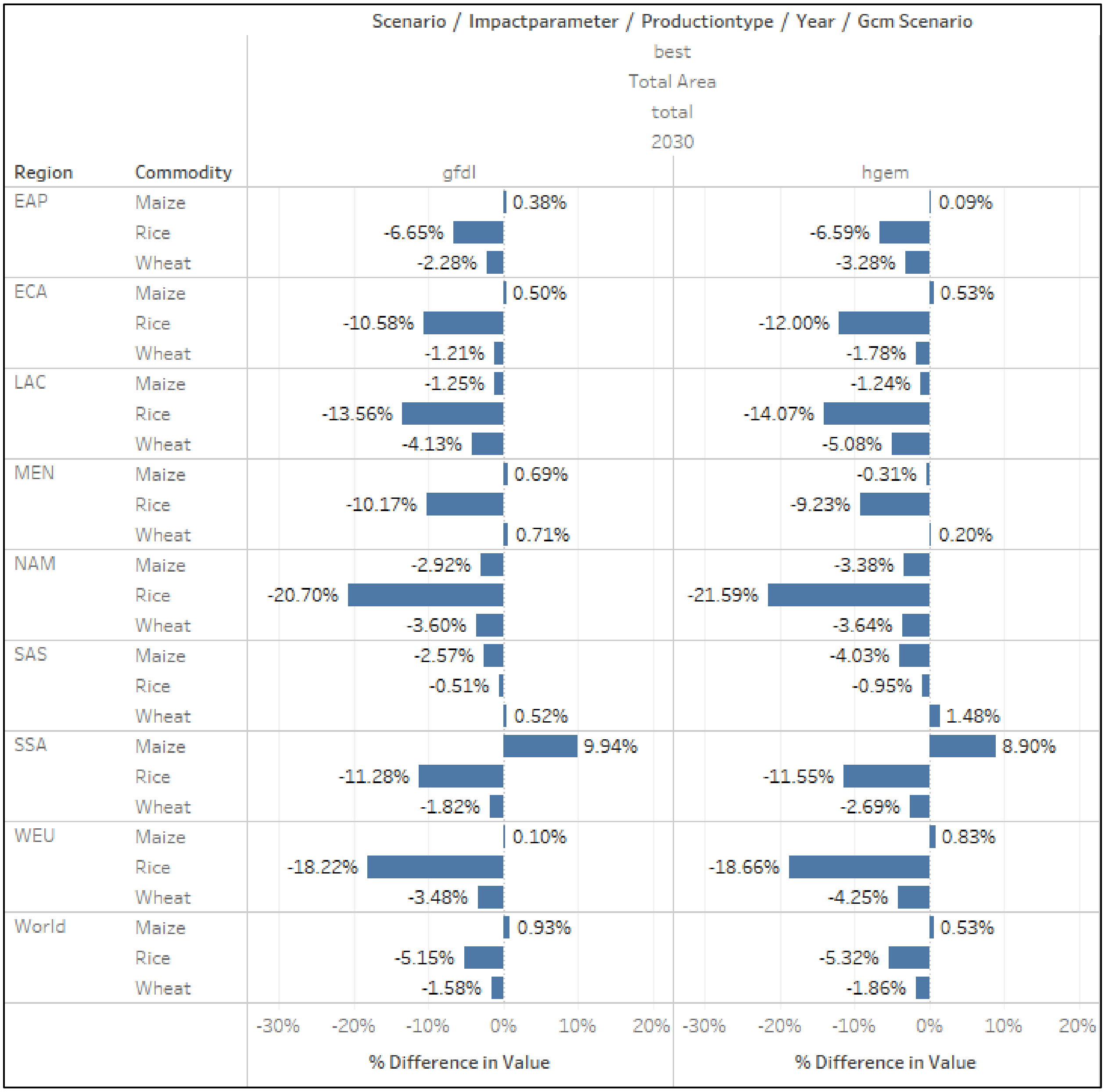
Figure A.3 Upper-bound scenario: 2010–2030—Changes in production by commodity and region



Source: Authors.

Note: EAP = East Asia and Pacific; ECA = Eastern Europe and Central Asia; LAC = Latin America and Caribbean; MEN = Middle East and North Africa; NAM = North America; SAS = South Asia; SSA = Africa south of the Sahara; WEU = Western Europe.

Figure A.4 Upper-bound scenario: 2010–2030—Changes in harvested area by commodity and regions



Source: Authors.

Note: EAP = East Asia and Pacific; ECA = Eastern Europe and Central Asia; LAC = Latin America and Caribbean; MEN = Middle East and North Africa; NAM = North America; SAS = South Asia; SSA = Africa south of the Sahara; WEU = Western Europe.

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