

# Land Use in the 21st Century: Contributing to the Global Public Good

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## Abstract

This paper focuses on the evolution of global public goods related to the world's land resources over the course of the 21st century, their potential impacts on the world's poorest households, as well as prospects for policy interventions aimed at enhancing these outcomes. It begins with global scale projections to 2100 of land use and associated goods and services, including food, fuel, timber, greenhouse gas emissions, carbon sequestration and biodiversity. This is followed by in-depth discussion of each of these services and the challenges of providing these public goods in sufficient quantities to advance societal welfare—especially that of the world's poorest households. The paper concludes with a discussion of policies aimed at promoting the provision of land-based public goods and how they could be altered to be more pro-poor. Within this context, the paper argues that access to geospatial analysis tools and information on climate, land use and tenure, poverty and environmental indicators will become increasingly valuable to both public and private decision makers.

## 1. Introduction and Historical Perspective

Land is arguably the world's most important natural resource. It provides a host of public and private goods and humankind has played a large role in shaping its evolution over the millennia. Ramankutty et al. (2006) point out that people have been involved in inducing land cover change since the beginning of human history. Today, about one-third of the world's land cover is devoted to agriculture, one-third to forests and one-fifth to savannas, grasslands and shrublands (Ramankutty, 2010). While the global area devoted to crops has changed only modestly in the past 50 years, the distribution of these croplands has changed much more dramatically (Ramankutty et al., 2008). Indeed, global land cover change accelerated to unprecedented levels during this time period (Lepers et al., 2005), and this, in turn, has had consequences for the associated ecosystem services available at local, regional and global scales. Much of the cropland expansion during the past half century has been in the tropics (Ramankutty et al., 2002). There is evidence that the cropland expansion in the tropics has come at the expense of closed tropical forests (Gibbs et al., 2010). These areas are particularly rich in biodiversity as well as carbon (West et al., 2010).

The question of global adequacy of the world's land resources to meet continuing growth in demand for food, fiber, fuel and other ecosystem services has important implications for the world's poor. The bulk of the world's poor reside in rural areas, and many of these households still “live off the land” in one way or another. Many are smallholder farmers, others are employed in agriculture or forestry activities

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and others still rely on hunting and gathering for a significant portion of their income and/or sustenance (Cavendish, 2000). Efforts to increase the provision of land-based public goods will affect these households directly, when they are either displaced (e.g. by a nature preserve) or when they are paid for providing these services themselves (e.g. for carbon sequestration or forest conservation). There are also important indirect effects that arise when the overall availability of land is altered, thereby affecting food prices and rural employment opportunities.

This paper begins with an overview of how global land use and the associated public and private goods and services are likely to change over the course of the 21st century. It then offers an in-depth analysis of key, land-based public goods (Table 1), including carbon sequestration, bioenergy, biodiversity, and institutions to facilitate climate adaptation, including information and analysis tools to adapt to the changing environment. The paper focuses on areas where under-provision of these public goods is likely and, in such cases, it discusses the potential for public policies, research and development assistance to enhance their provision.

## **2. The Evolving Global Supply and Demand for Land-based Goods and Services in the Twenty-first Century**

Before examining the specific public goods associated with global land use, it is useful to step back and evaluate how we expect global land use to change over the coming century. What are the fundamental drivers behind global land use and the associated goods and services? Towards this end, we draw on projections for global land use change and land-based greenhouse gas (GHG) emissions over the 21st century developed by Steinbuks and Hertel (2016) using the FABLE (Forestry Agriculture Biofuels Landuse and Environment) model. FABLE is a discrete, dynamic, partial equilibrium optimization model that runs at global scale and characterizes long run competition for land between food, biofuel, forest products, carbon sequestration and other land-based ecosystem services. FABLE allocates long run global land uses in order to maximize the discounted social value obtained from these land-based goods and services, subject to available technology and biophysical constraints, including the global land endowment and explicit growth functions for food crops, bioenergy crops and forests, by vintage. FABLE is “forward-looking,” which means that optimal land use change today is influenced by expectations of developments in the future, including energy prices, population and income growth, new technologies and government policies. In the baseline scenario, real fossil fuel costs rise at an annual rate of 3% (Energy Information Agency, 2010), population growth slows, plateauing at 10 billion people in 2100 (Bloom, 2011), global per capita income grows at about 2%/year and, in the absence of climate mitigation policies, GHG accumulation in the atmosphere causes global temperatures over agricultural areas to rise at an average rate of 0.3 degC/decade (Intergovernmental Panel on Climate Change (IPCC), 2007). (Given their inherent uncertainty, alternative paths for these underlying drivers of land use change will be explored later on.)

Figure 1(a) reports the evolving allocation of global agricultural and forest land use over the 21st century, according to the FABLE baseline. Area devoted to food production continues to rise to 2040, as demand growth, driven by rising population and dietary upgrading, outpaces productivity growth. However, by 2040, the combination of slowing population growth, improved productivity and competition from second generation biofuels, results in cropland devoted to food production declining after 2040, ending the century 12% below current levels. In contrast to

Table 1. *Global Public Goods Related to Land Use, Challenges Facing the Poor, and Associated Policy and Research Needs*

<i>Public good</i>	<i>Challenges—especially those facing the poor</i>	<i>Policy implications</i>	<i>Research needs</i>
Carbon sequestration (REDD)	Land tenure is key for contracting Sequestration can lead to higher food prices Market for carbon credits has collapsed	Establishing land tenure/titling Safety net policies for the poor Re-invigorate carbon markets	Improved mapping of land tenure Establishing REDD baseline and targeting payments Understanding impacts of large scale carbon sequestration on the poor
Bioenergy	Environmentally damaging land conversion Competition for land can lead to higher food prices Government policies/oil prices introduce uncertainty	Social value hinges on climate policy Investors require greater certainty	Comprehensive, social valuations of bioenergy must factor in all land uses as well as conversion costs
Biodiversity and other environmental services (PES)	Absence of land title Land payments by-pass poor High fixed costs of contracting Measurement of environmental services	Establishing land tenure/titling Outreach to poor; access to credit Progressive payment schedules Institutional innovations	Estimating future demand for environmental services Identifying natural areas to be set-aside for future generations
Policies and institutions for climate adaptation	Climate impacts on non-market goods Credit constraints and market access Limited scope for altering crop calendar in tropics Underinvestment in R&D in tropics Climate change destroys value of local knowledge	Improved integration into commodity markets Improved access to credit Increased support for R&D Improved water management Funding for weather forecasting coupled with improved outreach to farmers and marketing firms Public weather index insurance Micro-finance to allow poor to purchase insurance	Assess climate impacts in tropics and constraints to adaptation R&D on heat and drought tolerance; resistance to pests and disease Improved weather forecasts Understanding constraints to adoption of insurance by poor
Weather forecasts and index insurance	No buffer against losses Covariate shocks hit entire community Credit constraints limit subscription		

Source: Author's compilation.

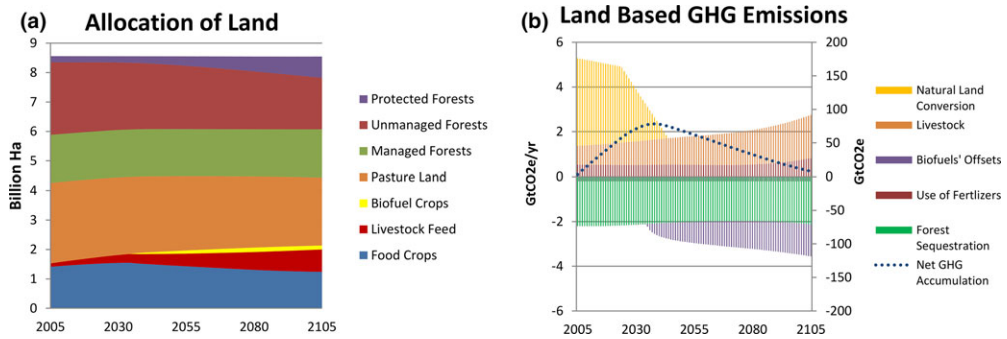


Figure 1. Optimal Paths of (a) Global Land Use and (b) GHG Emissions in the FABLE Model Baseline. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

Source: Steinbuks and Hertel (2016).

food crops, the area devoted to animal feed expands strongly over the coming century, while pasture area declines. This reflects the ongoing process of intensification in the livestock sector (Taheripour et al., 2013).

Under the baseline growth in fossil fuel prices, second generation biofuels become commercially viable in the late 2030s and expand to encompass 140 million hectares by 2100, assuming energy prices rise steadily to 2100. Managed forest area is stable, thanks to continuing innovations in the wood products sector, while protected forests (nature preserves and parks) grow strongly as developing countries' governments seek to enhance public access to these natural amenities and international efforts to preserve biodiversity expand. All of this squeezes those forest lands that are unmanaged and largely inaccessible and which decline by roughly 200 million hectares over the coming century.

In the absence of land-based climate mitigation policies, this pattern of land use change carries with it significant implications for GHG emissions, which are shown in Figure 1b. The major sources of cropland-related emissions between now and 2040 include conversion of natural lands for commercial purposes, as well as emissions from livestock and fertilizer use.<sup>1</sup> These GHG emissions dominate forest carbon sequestration until mid-century, when the combination of slowing population growth and continued agricultural productivity improvements bring an end to large scale, net cropland conversion. After this point, the world's land resources become a net carbon sink—first, owing to forest carbon sequestration, and second, because of carbon offsets from second generation biofuels that emerge in the context of the authors' baseline assumption of rising oil prices (based on the US Energy Information Administration (EIA) projections). Even in the absence of climate regulation, this model predicts that the world's land resources will be an important contributor to global carbon sequestration after mid-century.

Of course, given the many uncertainties surrounding specification of the baseline scenario, no model is going to deliver accurate predictions of global land use 50–100 years from now. Therefore, it is important to consider how socially optimal global land use would be affected by two of the major uncertainties facing the world today: climate change and energy prices. The left-hand panel (a) in Figure 2 shows how changes in the path of global temperature affect land use. At higher temperatures, food crop yields face a higher penalty and yields grow more slowly, therefore requiring more land area to meet global food demands. In contrast, second generation biofuels (e.g. switchgrass) thrive at higher temperatures (Brown

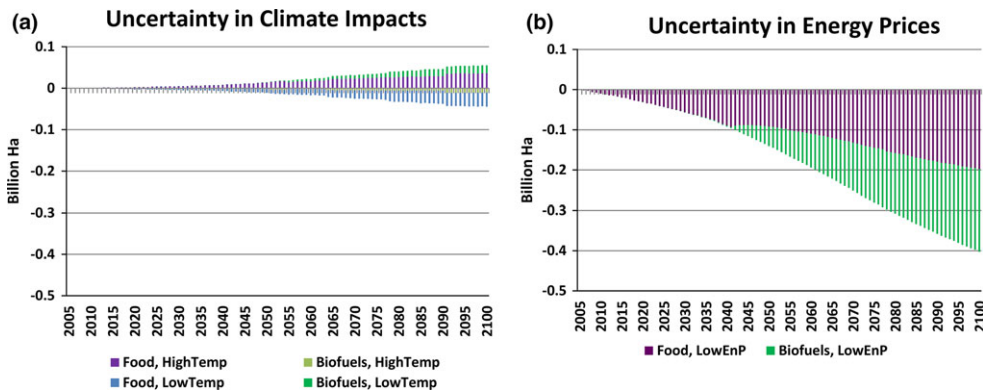


Figure 2. Land Use Changes Relative to Baseline Owing to Uncertainty in (a) Temperature and (b) Energy Prices. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

Source: Steinbuks and Hertel (2013).

et al., 2000) so that yields grow significantly faster than baseline and somewhat less land area is demanded for biofuels (although more is produced, as it becomes cheaper owing to the higher feedstock yields). Overall the food crop impacts dominate and the high temperature scenario generally results in greater land scarcity.

Energy prices are also an important source of uncertainty over the coming century. Figure 2(b) shows the effect of flat energy prices throughout the 21st century on optimal land use. Given developments in global oil markets since 2014, this scenario no longer seems far-fetched. In this case, second generation biofuels never become commercially viable and the associated land conversion no longer takes place, thereby reducing total cropland requirements in 2100, but cheap energy also has another important effect and this is to lower the cost of fertilizer.

Lower-priced fertilizer allows for greater intensification of production and higher yields, therefore resulting in less land required for food production. While the path is somewhat different, the end result in 2100 is quite similar in magnitude to that caused by the lack of competitiveness of second generation biofuels, namely 200 million hectares less crop land required in 2100. The combined impact of these two effects amounts to a reduction of 400 million hectares of cropland in 2100, relative to the baseline, suggesting that energy prices may be the most important “wildcard” of global cropland use in the 21st century (Steinbuks and Hertel, 2013).

In summary, even in the absence of policy interventions, we expect significant changes in the level and mix of public goods supplied by the world’s land resources over the coming century. We now turn to an in-depth discussion of the individual global public goods associated with land use, the extent to which they might be under-supplied and, in such cases, the policies that might encourage greater provision.

### 3. Public Goods Related to Land Use

*Carbon Sequestration: REDD+ (Reducing Emissions from Deforestation and Forest Degradation in Developing Countries, and the Role of Conservation, Sustainable Management of Forests, and Enhancement of Forest Carbon Stocks in Developing Countries)*

Agriculture, Forestry and Other Land use (AFOLU) accounts for roughly one-quarter of global GHG emissions (IPCC Working Group III Assessment Report 5 (WGIII AR5), 2014). The majority of these emissions come from land use change, including deforestation and the conversion of peat bogs to agriculture. Therefore, appropriate management of the world's soils and forests can contribute significantly to slowing the rate of CO<sub>2</sub> accumulation in the atmosphere. Reilly et al. (2012) simulate the case where there is perfect pricing of carbon associated with land use (soils as well as plants), in addition to pricing carbon from energy combustion. They estimate a net gain over the 21st century of 178 petagrams of carbon.<sup>2</sup> Golub et al. (2009) estimate that, in the near term, forest carbon sequestration could supply up to 50% of the annual flow of globally efficient greenhouse gas (GHG) abatement. Sohngen (2010) estimates that inclusion of forest carbon sequestration within an optimal climate policy could cut the price of carbon by nearly half in 2100. Clearly there is much to be gained by providing incentives for individual decision makers to modify land cover and land use practices to accommodate additional carbon stocks in the soil and above-ground biomass.

However, the practical implementation of such policies can be challenging. To see one reason why this is the case, let us return to the FABLE model and explore the implications of a land-based GHG emissions constraint, pre-announced, but not starting until 2025 and aiming to cut emissions by 60% by 2100. Figure 3(a) plots the change in global land use owing to this policy. The biggest reductions are in pasture land and crops grown for feedstuffs, with a small reduction in land allocated to food crops. In place of these land uses, there is strong growth in managed forests, with fewer unmanaged forests being converted to other uses so that this land use rises above its baseline level). The optimal rotation in these managed forests is also lengthened in order to increase the forest carbon stock. Cellulosic biofuel feedstocks increase, relative to baseline, as these generate GHG emissions offsets owing to the displacement of fossil fuels in the provision of energy services.

Figure 3(b) reports how a global climate policy encompassing land-based emissions, announced in 2004, but not implemented until 2025, alters the world's land-based GHG profile. The most striking effect is the tendency to immediately convert additional forest lands, as well as altering the vintage profile of the managed forests, in anticipation of the stringent policy coming into effect in 2025.

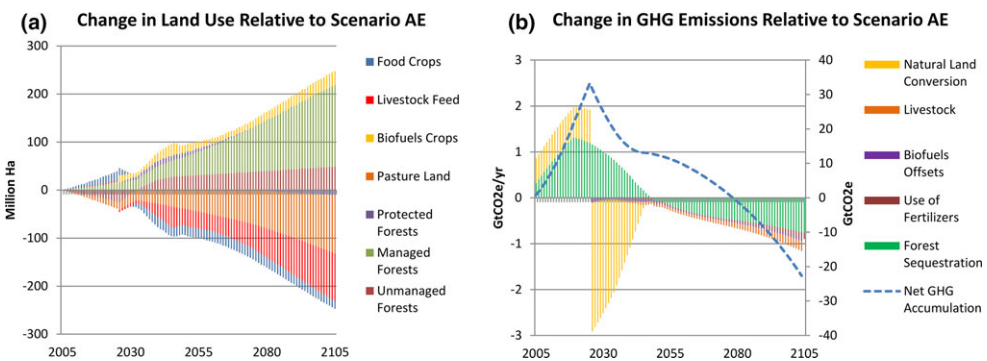


Figure 3. Impact of Pre-announced GHG Regulation Implemented in 2025 on: (a) Global Land Use and (b) GHG Emissions in the FABLE Model. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

Source: Steinbuks and Hertel (2016).

This is commonly referred to as the “green paradox” (Sinn, 2008). Once the policy starts in 2025, land conversion comes to a stop and net emissions switch from +2GT/year to −3GT/year. However, net GHG accumulations, relative to baseline, do not decline until nearly 2080. This highlights the ineffectiveness of pre-announced mitigation policies in the context of long-term land use decisions.

While research on terrestrial carbon sequestration policies is still in its infancy, there are a significant number of bottom-up initiatives underway presently and the number is growing each year. Hamrick (2015) offers an annual update of carbon sequestration projects, noting that, since these tracking efforts began, voluntary markets have avoided one billion tons of carbon dioxide emissions equivalent. While most of the expenditures on these projects have taken place in the USA, Brazil, Turkey, India, Kenya and China have also been quite active, with total demand for voluntary offsets growing by 14% in 2014. In earlier reports, these annual reviews have found that the majority of the contracts are with private land owners. Given the excess supply of carbon contracts, relative to demand, purchasers have gravitated toward the easier contracts—which tend to be with the privately held lands. Indeed, the data on the price of individual contracts by land tenure type suggests that sequestration on collectively held lands is roughly twice as costly as on privately held lands (Peters-Stanley et al., 2012).

Unruh (2008) argues that, despite high biophysical potential, land tenure is a critical barrier to successful carbon sequestration policies—particularly in Africa. He highlights the social, legal and economic disconnect between statutory land tenure, which applies in theory and the customary systems that are predominant in practice, but which are not recognized by formal laws. As a consequence, governments often “ignore customary tenure systems and regard such areas as part of the public domain, while at the same time lacking the capacity to enforce such a claim or resolve the problems that such a claim produces” (Unruh, 2008). Others are more optimistic about the potential for carbon sequestration contracts on communal lands and the empirical evidence suggests that progress is being made in the establishment of carbon sequestration contracts on communally held lands. Peters-Stanley et al. (2012) report a strong increase in the number of contracts with collectively held lands from 2010 to 2011. Barbier and Tesfaw (2012) point out that sequestration may be an area where such contracting on communal lands could work well in Africa, precisely because tree planting shows a sustained commitment to the land and is therefore one of the ways in which individuals can secure long-run use rights in the context of communally held land.<sup>3</sup>

Even when the carbon sequestration payments do not reach the poor directly, they can have an impact on poverty indirectly through higher food prices, impacts on rural wages and increased land values. Hussein et al. (2013) explore the distributional impacts of a global forest carbon sequestration policy. They conclude that most of the benefits of this policy would flow to landowners (either private or collective owners of the land). Since the poor generally control relatively little land (and when they do, it is often land of lower value), they are unlikely to benefit greatly from appreciating land value. Therefore, the predominant impact of a global forest carbon sequestration policy on the poor is likely to be through higher food prices. The authors find that this results in poverty increases in 11 of their 14 sample countries, with most of the impact being driven by forest carbon sequestration in the tropics (Hussein et al., 2013). However, this work is hardly definitive and suggests the need for more research into the poverty impacts of large scale carbon sequestration initiatives (Table 1).

*Bio-based Energy*

Given the growing global priority being placed on climate mitigation, there continues to be strong interest in moving from a fossil-fuel based economy toward a bio-economy in which an increasing share of liquid fuel, as well as electric power comes from plant material, the growing of which sequesters carbon. In a perfect world, the carbon emitted from such bio-combustion would be exactly offset by the sequestration associated with the growing of these plants, or, in the case of bioenergy with carbon dioxide capture and storage, it becomes a carbon sink (IPCC, 2014b). However, experience to date with bioenergy has been mixed. In the USA, assessments of corn ethanol went from declaring the Renewable Fuel Standard to be a win-win-win for the environmental-agricultural-national security nexus in 2006 (Farrell, 2006) to a global environmental disaster just two years later (Searchinger et al., 2008), to a marginally beneficial, but economically costly means of obtaining improvements in environmental quality (Hertel et al., 2010b). Most of the controversy has focused on the global land use impacts of expanding so-called “first generation” biofuel production, which uses food crops as feedstock (Hertel and Tyner, 2013). These conclusions contrast sharply with those of the IAM (Integrated Assessment Modeling) studies focusing on long run, land-based mitigation options (Creutzig et al., 2012). The latter literature suggests that bioenergy could provide up to 15% of total primary energy requirements by 2100 (Rose et al., 2012). This raises a question of inter-temporal inconsistency? How does one transition from a situation in which bioenergy is destroying the environment, to one in which it is a key element of a sustainability strategy?

Since the two groups of literature draw on vastly different models, baseline scenarios and policy assumptions, it is hard to compare them directly. The intertemporal FABLE model offers one vehicle for exploring the evolution of biofuels over the coming century. Consider two alternative futures: one in which these technologies are not available and one in which they are present. By solving for the optimal long run pattern of global land use twice, once without and once with the technology, we can gain some understanding of how the second generation biofuel technology might influence global land use as well as the provision of the associated land-based goods and services. Hertel et al. (2013) used an early version of FABLE to examine this question. Figure 4(a) reports the change in global land use associated with the introduction of second generation technology into the long run optimization decision. As with Figure 1, it does not become optimal for second generation technology to be used until 2040. However, under the baseline assumption about oil prices, the area devoted to cellulosic feedstocks grows rapidly thereafter—at the expense of food crops as well as forests. Figure 4(b) shows the implications for GHG emissions, which rise as a result of land conversion undertaken in anticipation of the new technology coming online, but which eventually decline, contributing to negative net accumulation by the 2080s.

Hertel et al. (2015) employ a more recent version of FABLE to evaluate the social value of second generation biofuels technology using the “difference in differences” approach—i.e. comparing the difference between the differenced simulations across alternative scenarios. Their results are reported in Figure 5. The bars in this figure report the discounted present value (US\$ per capita) of the future stream of global benefits and costs associated with second generation biofuel technology, obtained by solving the model twice and differencing the results. Each vertical bar refers to a different future scenario, beginning with the baseline described above in Figure 1 and then altering a key baseline assumption. These



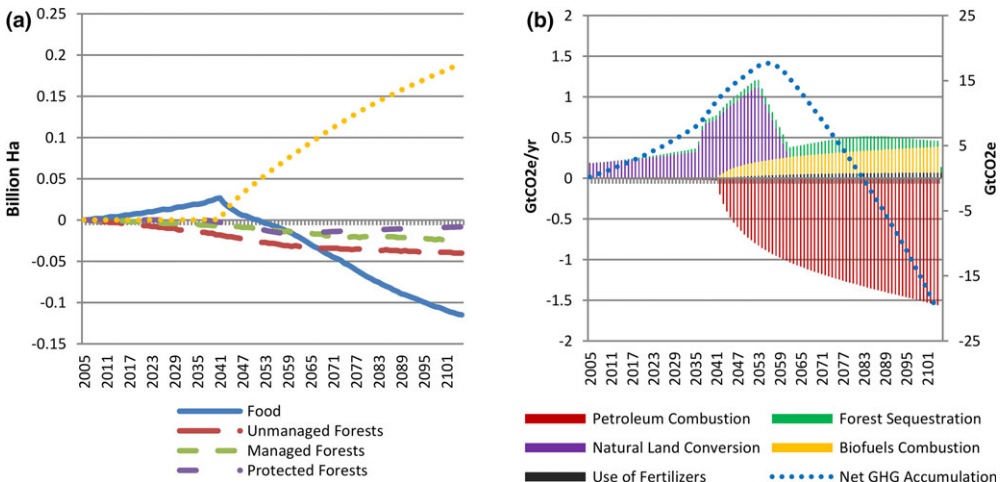


Figure 4. Impact of Introducing Second Generation Biofuels on: (a) Global Land Use and (c) GHG Emissions in the FABLE Model Baseline. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

Source: Hertel et al. (2013).

alternative scenarios include: the presence of climate change impacts (recall Figure 2a), GHG regulation (Figure 3), flat energy prices (Figure 2b), slower economic growth and higher population growth. The circles in each bar report the total welfare change under three different technology assumptions (baseline, optimistic and pessimistic) and the segments decompose the total change into portions attributable to individual factors. The most important welfare contributor is petroleum cost savings, following by biofuel conversion costs; however, forgone consumption and land competition-related costs can also play an important role.

It is interesting to note, from the results in Figure 5, the relatively robust nature of the global welfare gains to variation in the assumption about second generation biofuel technology. Given the commercially immature nature of this technology (nearly all efforts to date have been pilot projects, since commercial efforts are extremely expensive), this is an important finding. The social valuation also appears robust to assumptions about climate impacts as well as global economic and population growth rates. This is in sharp contrast to climate regulation and energy prices where the results in Figure 5 clearly show that these two factors are critically important in determining the social value of biofuels over the coming century. Within this context, most of the added benefit from second generation biofuels in the presence of climate regulation comes from the additional consumption of land-based goods and services. This is consumption that would have been sacrificed for the sake of emissions reductions in the absence of the fossil fuel offsets offered by second generation biofuels. If society become serious about limiting land-based GHG emissions, then the social value of second generation biofuels nearly doubles. In contrast, if the social opportunity cost of oil remains low throughout the century, biofuels have virtually no value to society. Given the uncertainty in both climate regulation and oil prices, these findings highlight the challenge in assessing the value of public investment in second generation biofuel technology.

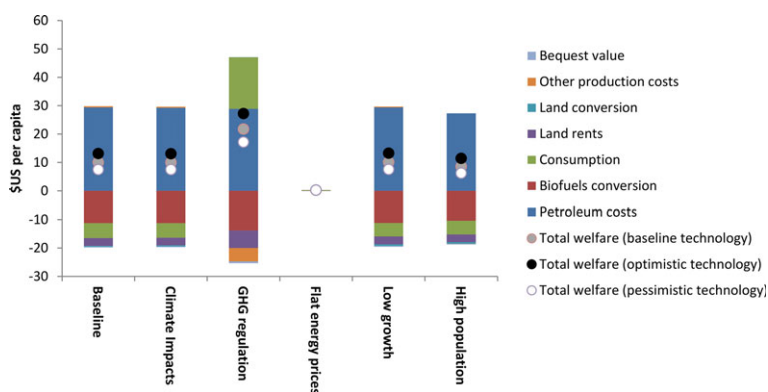


Figure 5. Valuation of Second Generation Biofuel Conversion Technology in US Dollars Per Capita. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)] Source: Hertel et al. (2015).

### Biodiversity and Payments for Environmental Services

Natural lands offer a range of environmental services, many of which are associated with the term “biodiversity.” Biodiversity—and particularly its valuation—has been notoriously difficult to measure. The FABLE model incorporates valuation estimates from Costanza et al. (1997) who estimated values for 17 ecosystem services from 16 ecosystem types, at global scale. There has also been additional progress at a regional scale, focusing on more specific ecosystem services. Strand et al. (2014) conduct a survey of experts on ecosystem valuation and conclude that the willingness to pay for preservation of the Amazon rainforest ranges from US\$4–\$36 in Asia to nearly US\$100/household/year in Canada, Germany and Norway. Pollination services have received particularly close attention by large teams of ecologists. Seventy percent of global crops depend on pollination services (Klein et al., 2007) and there is evidence that these are non-linearly (negatively) associated with distance from the natural habitat. The removal of natural habitat from the proximity of crops translates into lower yields and lower quality fruit. In a study of coffee cultivation in Costa Rica, the benefits of proximity to natural forests were estimated to be about US\$700/hectare (Ricketts et al., 2004). Nearly 100 of the world’s most important fruit, vegetable and seed crops are dependent upon animal pollination (Klein et al., 2007) and loss of these ecosystem services could reduce global food production by between 3% and 8% (Aizen et al., 2009).

Given society’s interest in preserving biodiversity, the question is how to promote this outcome in the context of the many constraints faced by farmers and other landowners. This is where Payments for Environmental Services (PES) come into the picture. The global annual size of the market for biodiversity conservation has grown to nearly US\$3 billion (Madsen et al., 2010) and there is now quite a large literature on PES programs (Gong et al., 2013). One of the most successful examples is the “Socio Bosque” program in Ecuador. While the theory of PES suggests that payments should vary over space and time according to the opportunity cost of the land in competing uses, this is often difficult to achieve in practice. In the case of Socio Bosque, data limitations and the desire for transparency dictated instead a simple “progressive” structure in which the first 50 hectares enrolled receives US\$30/hectares/year for the 20-year duration of the

contract, the second 50 hectares (i.e. 51–100 hectares) receives US\$20/hectares/year and so on. As a result, the bulk of the community payments (80%), when expressed on a per household basis, are under US\$500/year (De Koning et al., 2011). These community payments are used for investments that address basic needs, as well as for productive activities such as agriculture and community banking. However, in order to enroll in Socio Bosque, a formal land title is needed and this has precluded involvement by many poor households and communities who have not yet formalized their land ownership (De Koning et al., 2011). In addition, poor households are poor, in part because of their limited access to land, which in turn limits their potential participation in this land-based contracting arrangement. Adding to this the high transaction costs associated with reaching the poor and the fact that much of their land is communally held, it is not surprising that PES participation rates by the poor are quite low (Pagiola et al., 2005).

In their reviews of the challenges of implementing national PES systems in developing countries, Angelsen (2013) and Gong et al. (2013) highlight several other issues. The first is the challenge of defining and measuring the service provided. Given the spatial heterogeneity of ecological systems throughout the tropics, accurate measurement of environmental services can be extremely costly—where do you draw the line? Angelsen (2013) highlights the challenge of contract design in light of asymmetric information that gives rise to both moral hazard and adverse selection problems. Gong et al. (2013) conclude their review of PES programs by noting that: “The desire to simultaneously obtain a maximum level of environmental benefits, an increase in economic efficiency and a reduction in inequality is a laudable goal, but project developers must realize there are trade-offs, tough decisions have to be made.”

### *Climate and Land-based Goods and Services in the 21st Century*

Regardless of progress with carbon sequestration and other forms of GHG mitigation in the near future, the dye is already cast for significant warming of the Earth's surface between now and 2050 (IPCC, 2014a). Between the physical momentum created by the accumulation of GHGs in the Earth's atmosphere and the economic momentum stemming from the construction of coal-fired power plants, the rapidly growing stock of automobiles in China, India and other developing countries, and, more generally, the growing global demands posed by adding two billion more consumers, there is little doubt that climate change will accelerate. Even if the aggregated, global-scale land use impacts are modest (Figure 2a), there will be tremendous heterogeneity in regional and local impacts and these local impacts are of particular importance to the world's poorest countries and the most vulnerable segments of their populations (Hallegatte et al., 2016). This raises the question of whether there are public goods and services that might aid in such adaptation.

*Impacts on non-market goods and services*<sup>4</sup> While most of the literature on land-based climate impacts focuses on commercial production, climate change can affect the poor through its impacts on the availability of non-priced goods such as renewable natural resource endowments that may be quite sensitive to climate change. This is further complicated by the fact that ownership is often communal (Cavendish, 2000). It is also common for these types of goods to be nontraded, even in local markets. Examples of natural resource goods that are relevant to

household consumption, production and asset accumulation include: wild foods, medicines, construction materials, energy sources, furnishings, tools and utensils, fertilizer, grazing and fodder, clay for pottery, timber and mineral resources. As average and maximum temperatures increase, the productivity and viability of plant species change, particularly above the threshold temperature of 35°C (Schlenker and Roberts, 2006). Thus climate change is likely to cause species loss as well as altering the types of fauna supported by an ecosystem (Walther et al., 2002; McCarty, 2001). Empirical evidence from household surveys in Zimbabwe estimate that poor households derive as much as 40% or more of their incomes from environmental goods (Cavendish, 2000) and 24% of incomes in Peru (Takasaki et al., 2004). On the whole, the contribution to poor incomes from environmental goods can reach levels equal to or greater than income from cash crop production, unskilled labor wages, small businesses and crafts (Cavendish 2000), so these households will be vulnerable to potential reductions in the availability of these goods in the wake of climate change.

*Agricultural impacts* The IPCC estimates that temperature increases over the world's farmlands will be on the order of 0.3–0.4 degC per decade, leading to likely negative impacts on crop yields in the 2030s and “median yield impacts of 0 to –2%/decade over the remainder of the century” (IPCC, 2014a).

One of the most troubling aspects of the analyses of climate change impacts undertaken thus far is the fact that most of the crop models used capture only about half of the key mechanisms by which temperature affects crop yields and the elements that are most generally omitted are those that are likely to be felt most severely in the tropics (Hertel and Lobell, 2012). This suggests that the impacts of higher temperatures on crop yields in the tropics are more likely to be at the extreme end of the potential range. Therefore, agricultural adaptation to higher temperatures will be especially important for farmers in the tropics.

It is useful to consider two distinct aspects of agricultural adaptation: biophysical and economic. Deryng et al. (2011) find that the scope for biophysical adaptation of maize, soybean and spring wheat to higher temperatures (+2 degC) is much lower in the tropics than in the temperate zones. This is due to the fact that planting dates in the tropics are typically dictated by rainfall and not temperature and therefore cannot be easily adjusted in the face of higher temperatures as might be the case in temperate regions. Also, in the tropics crops are already being grown at, or above, their optimal temperature range. Research into on-farm economic adaptation is much more limited than for biophysical adaptations (Antle and Capalbo, 2010), owing to the difficulty of generating experimental data, coupled with the fact that observational research must rely on responses to the relatively modest changes in climate to date. One point that is clear is that farm-level economic adaptation will hinge critically on access to markets, including those for credit, purchased inputs, knowledge about new practices and markets for potentially new products (Lybbert and Sumner, 2012). Unfortunately, limited access to inputs and credit is one of the reasons why many of the world's poor—particularly those living in rural areas—remain poor. In summary, it appears that researchers are likely understating the adverse impacts of higher temperatures on crop yields in the tropics, even as they overstate the potential for adaptation in the poorest countries. What public goods might enhance adaptation potential in the tropics?

*Market integration as a public good* In an important historical study of rainfall and famine in colonial India, Burgess and Donaldson (2010) find that the arrival of railroads—and hence ready access to national markets—in Indian districts “dramatically constrained the ability of rainfall shocks to cause famines in colonial India” (p. 450). This finding further underscores the potential contribution of “climate smart” investments in infrastructure. Of course, the extent to which markets actually facilitate adaptation also depends on government policies. Verma et al. (2014) examine the interplay between policies and market-based adaptations in coping with the agricultural impacts of increasingly frequent and intense extreme climate events. They consider two types of integration: intersectoral market integration (i.e. closer integration of agricultural and energy markets through biofuels) and international market integration (i.e. more intense trade relations between countries). They find that, when it is market-driven, intersectoral integration offers the potential for mitigating a significant amount of the commodity price volatility emanating from the corn markets. However, if this integration is achieved via mandates (e.g. the US biofuels mandate for ethanol), then the opposite is true, with government-mandated integration exacerbating corn price volatility under climate change. On the international front, the authors estimate the benefits of closer integration through stronger international trade disciplines. They find that this type of policy reform also offers an avenue to reduced market volatility.

Baldos and Hertel (2015) find that international market integration can also moderate the long run impacts of climate change on global malnutrition—particularly if the most pessimistic projections of climate impacts on agriculture are realized. By combining results from the Hadley Centre Global Environmental Model (HADGEM) Global Circulation Model with the Lund–Potsdam–Jenna Managed Land (LPJmL) crop model and ignoring the uncertain gains from CO<sub>2</sub> fertilization, they find that this worst-case climate change scenario could increase malnutrition in South Asia by nearly 120% in 2050, relative to their no-climate change, baseline. However, if, instead of the currently segmented markets for global crops, global crop markets were fully integrated, this effect would be reduced to a 40% rise in malnutrition, relative to baseline. So fluid international trade is a valuable public good in the context of climate adaptation.

*Improving weather forecasts and providing weather-related insurance*<sup>5</sup> Farm households’ strategic decisions are influenced by many factors including risk aversion, wealth levels, climate variability, the surrounding policy and institutional environment. However, one critical, yet often overlooked factor is the availability of information. As noted by Quiggin and Horowitz (2003): “Another way of looking at [climate change] is that the information held by economic actors about the climate becomes more diffuse, and hence less valuable in the presence of a new source of uncertainty. Thus climate change may be regarded as destroying information ... [such as] the informal knowledge of particular local climates that is acquired by attentive individuals over a long period.”

Because sensitivity to climate risks decreases with increasing wealth, policies to provide better information and thereby reduce the effective level of climate risk, should be particularly beneficial for poor farmers in the context of increasing climate extremes. Empirical studies, however, offer conflicting assessments of the potential for either of these types of investments in climate change adaptation to affect the decision-making process of the poor. Gine et al. (2007) found that

farmers in India with fewer risk-coping mechanisms invested more effort in acquiring accurate weather prediction information. Other studies, however, have concluded that farmers give relatively little weight to weather forecasts when making planting decisions owing to poor spatial and temporal resolution, and lack of trust for the institution issuing the forecast. Letson et al. (2001) found that, while older farmers in Argentina relied less on climate projections, their experience of farming during the 1997/98 El Niño event introduced a greater confidence in climate projections. This suggests that farmers may increase their demand for accurate climate forecasts in the future as climate change renders their traditional information sources and experience less reliable.

Increasing the usefulness of modern climate forecasts depends on “developing focused knowledge about which forecast information is potentially useful for which recipients, about how these recipients process the information, and about the characteristics of effective-information delivery systems and messages for meeting the needs of particular types of recipients” (Stern and Easterling, 1999). The majority of herders studied by Luseno et al. (2003) had no access to modern forecasts transmitted through radio and newspapers. This suggests an opportunity for an extension of services from agricultural ministries, non-governmental organizations (NGOs), or donor agencies to work with local farmer groups to develop and deliver effective forecasts targeted at the poorest groups. In their study of the value of season climate forecasts in Mozambique, Arndt and Bacou (2000) suggest that getting this information to those working in the marketing system may have even greater value than that generated by getting it to the farmers.

Insurance is the canonical solution for managing risks such as changing climate conditions. Yet evidence suggests that the poor rarely include insurance as one of their strategies for diversifying risks. This lack of insurance can be partially explained by undeveloped insurance markets in many rural areas. However, even when insurance markets exist, the poor do not always choose to purchase insurance (Kiviat, 2009). One method of increasing insurance coverage for the poor is to provide public weather index insurance. Index insurance pays out when certain trigger events occur, such as rainfall levels fail to meet an established threshold. With the increased frequency and availability of satellite imagery, weather index insurance is increasingly based on remote sensing (Lybbert and Sumner, 2012). It is argued that weather insurance must be provided as a public good because the risks from weather events are highly correlated across households. Further, publicly provided insurance has low transaction costs, can be more transparent than private insurance, has low administrative burdens, can provide rapid payouts and minimizes asymmetric information problems (Gine et al., 2008). However, the evidence to date on the adoption of index insurance by poor farmers suggests that wealthier households are more likely to purchase weather insurance, as credit constraints were a significant barrier for the poor (Gine et al., 2008). Indeed, Binswanger-Mkhize (2012) argues that it is impossible to think about scaling up index insurance for the poor, simply because they are credit constrained and cannot pay out the money before planting in order to buy insurance that will only pay them after harvest.

*Research and development for adaptation* The public good that has most profoundly shaped global land use over the past century is agricultural research and development, and many argue that this has great potential for facilitating adaptation to climate change. Nonetheless, there has been a slowdown in publicly

funded research in some regions over the two decades from 1985–2005 (Alston et al. 2009). This was particularly pronounced in the 1990s. Since 2000, public spending on agricultural R&D has picked up again, increasing by 22% to 2008. Over the same period, global private spending on R&D (about one-fifth of the global total) has risen even faster—by 26% (Beintema et al., 2011). While this has been led by strong growth in China, India and Brazil, public agricultural R&D in low-income countries—particularly those in East Africa—has also grown over the period, averaging 2.1%/year (Beintema et al., 2011) and, after a long period of slow growth, the same report documents a 41% increase in real spending by the CGIAR Consortium (formerly the Consultative Group for International Agricultural Research). This rebound in investment is good news, given the long lag-time between investment, innovation, commercialization and adoption of new technologies, e.g. 20 years for straightforward improvements and more than 70 years for hybrid corn (Alston et al., 2008).

Which types of research and development (R&D) investments are likely to be most important in the context of a changing climate? Hertel and Lobell (2012) argue in favor of investing in innovations that have high value under the early 21st century climate, but which may have even greater value under a future climate. For example, crop varieties that exhibit heat and drought tolerance deserve high priority in light of projected higher temperatures, increased heat waves and longer periods of continuous dry days but, somewhat ironically, cold tolerance may also be important, as this will facilitate the migration of crops to higher latitudes in an effort to adjust the growing season and avoid extreme heat. Similarly other technologies that permit earlier planting will be more valuable under a future climate, as will crop varieties that are tolerant to rainfall inundations. Finally, improved pest and disease resistance will be important, as climate change is expected to favor pests and invasive species in many of the world's ecosystems (Ziska and Dukes, 2011). In many cases, the tools for achieving these new varietal traits will come from biotechnology (Lybbert and Sumner, 2012). For example, pest-resistant *Bacillus thuringiensis* (Bt) crops have played an important role in reducing costs and increasing yields in many parts of the world, as has herbicide tolerance.

#### 4. Policy Implications

##### *Advancing Global Carbon Sequestration*

With this background in mind, what can aid agencies do to promote local, national and particularly global public goods associated with land use? First consider the underprovision of terrestrial carbon sequestration services. At present, the supply of sequestration services vastly exceeds the demand and the price has collapsed. Nearly all of the projects moving ahead in this area are voluntary in nature—as opposed to being tied to compliance standards. This greatly limits growth potential. However, these problems notwithstanding, the REDD+ experiment must be seen as an important innovation—one that deserves to be further refined and built upon. Looking forward and building on the momentum arising out of the 2015, Conference of Parties to the United Nations Framework Convention on Climate Change (UNFCCC-COP-21) meeting in Paris, optimists cannot help but believe that the world must eventually reach a comprehensive new agreement to limit GHG emissions and when this happens, we will once again be drawn to REDD+ as

a low cost option for achieving GHG mitigation. Therefore, it will be important to have a viable, global REDD+ program ready for implementation, so that it could be rolled out relatively quickly. As global institutional innovations go, this concept is still quite young and therefore, not surprisingly, has many limitations. Angelsen (2013) identifies several of the key limitations.<sup>6</sup> The first is the determination of reference levels—how do we know that deforestation rates have actually dropped? This is particularly difficult in light of the fact that baseline deforestation rates hinge on a variety of economic and political variables that are themselves nearly impossible to forecast. A second problem has to do with the interaction between REDD+ programs and other abatement incentives—most notably fossil fuel combustion. When REDD+ is included in a larger basket of mitigation options, there is concern that it will dilute the stringency of the overall emissions constraint. A third problem falls into the more general category of implementation of performance-based aid when the funding agency is evaluated on the successful disbursement of funds and not on the outcome of the project. What do you do if program participants do not comply? Addressing these challenges in a serious fashion, via a set of carefully monitored case studies would be a worthy activity for foreign assistance aimed at ultimately facilitating an operational program to deliver this global public good with a global scale program.

### *Regional and Local Environmental Services*

As with REDD+, securing funding for PES programs has been a continuing challenge. Funds can come from the national government (as is the case with Socio Bosque). They can come in the form of foreign aid, administered by national programs. Or funds can come in the form of foreign aid for specific projects—a feature often preferred by results-oriented donors. Alternatively, support can come from voluntary markets in which individuals or corporations are simply seeking to “do the right thing.” In the case of the China Green Carbon Foundation, the national government is involved in launching an initiative that then taps into funds from the private sector (Gong et al., 2013). Finally, in some cases PES schemes are user financed—for example the Water Trust Funds in Ecuador, Colombia and Peru, which seek to connect payments from urban water users to rural landowners providing the watershed services (Stanton et al., 2010).

Given the foregoing projections of increased global demand for land-based ecosystem services by the end of this century, there is great merit in putting in place today institutions and tools for delivery of future public goods. However, unlike carbon sequestration, many of these are local or national in nature. Here, the role of foreign aid is more likely to be in the background. Emphasis should be on building capacity for local institutions to manage their natural resources in a manner consistent with their own goals and long-run aspirations. As part of such a planning effort, assistance in the establishment of national parks in low and lower-middle income countries would be a valuable, far-sighted use of public and private foreign assistance. While the demand for such amenities may not be large among households living at the subsistence level today, we know that the demand for such amenities will grow strongly with income and, by mid-century, such parks, and the associated ecological biodiversity that is preserved, will be very meaningful for their children and grandchildren. Yet the land that can offer such amenities is being rapidly developed and degraded in many parts of the developing world, making future establishment of natural reserves and parks difficult, if not impossible.



Providing resources—and a voice—for these future generations of citizens in the developing world would be a worthy activity. While this is already an area in which some private foundations and NGOs are actively engaged, the level of investment that they are able to make is just a drop in the bucket compared with the level of demand for such amenities we will see from the 10+ billion people expected to populate this planet in 2100.

### *Improving Global Land Governance*

In addition to efforts devoted to sorting out the practical implementation and support of carbon sequestration and local environmental services, there are other investments that could be made today, and which will improve potential outcomes from future programs aimed at delivering public goods associated with land use. One of these is land tenure and titling. While REDD+ may never become a poverty-friendly program, the opportunities for low-income communities and households to benefit from this and other PES programs will likely hinge on their ability to document legal title to the land. Therefore, aggressive investments in land titling today will position such communities to benefit in the future from such programs. Such investments will also yield additional benefits that come with households or communities having formal title to their land, including: access to credit, improved incentives for managing the land and increased likelihood of long term investments in land improvements.

Land titling may be viewed as one dimension of the broader questions of land governance—an issue that has received greater attention subsequent to the apparent “land grab” precipitated by the commodity crisis of 2007/2008 (Deininger and Byerlee, 2010). As a consequence, the World Bank has initiated the Land Governance Assessment Framework (LGAF) described in Deininger et al. (2012). This framework is based on the idea that, despite the inherently local nature of land governance, there are benefits from having an international framework through which to evaluate programs, identify global best practice and to identify promising policy reforms. They focus on several broad areas in which policy intervention may be relevant for delivering improved land governance. The first of these is the legal and institutional framework and the extent to which existing land rights are legally recognized, documented and enforced. Second, they consider land use planning, management and taxation. Transparent and equitable taxes, land use restrictions based on the public interest and an efficient and transparent planning process are key here. The third area of focus for the LGAF is the management of public land. Finally, the authors note the need for affordable, unbiased mechanisms for the resolution of the inevitable disputes.

### *Investing in Climate Adaptation*

In light of the inexorable changes in climate that the world is facing, investment in climate adaptation certainly deserves attention. High on the list of public goods related to adaptation is research aimed at maintaining productivity of land-based activities in the face of higher average temperatures and increasingly frequent and intense weather events. Heat and drought tolerance will be important, as will cold tolerance (to permit early planting), tolerance to flooding and pest and disease resistance. To the extent that yield losses can be avoided, these improved varieties will not only enhance food security, but also environmental security, as the area

devoted to world agriculture can be restrained, thereby avoiding excessive land conversion. Where adequate heat and drought tolerance are not forthcoming, supplementary irrigation will be a key vehicle for adaptation. By providing moisture during critical periods in the growing season, as well as cooling plants through evapo-transpiration, irrigation can allow producers to avoid catastrophic losses. While irrigation is a private good, the institutions surrounding water management in many countries result in inferior allocations of what is becoming an increasingly precious resource. Reforming these institutions and assisting communities in finding ways to improve the efficiency with which they manage their water resources is another area in which investments will bear high returns in the future.

In the absence of successful on-farm adaptation, crop market volatility is expected to increase—in some cases quite significantly (Diffenbaugh et al., 2012). This will raise the value of being able to “arbitrage” commodities across space and time. One of the companion papers in this volume discusses commodity storage options that allow for arbitrage over time. However, equally, and perhaps more important, is the ability to move commodities geographically in response to regional shortages. For this to be effective adequate infrastructure is needed. This is an area of investment in which foreign assistance—often mediated by the development banks—has a long track record. Such investments are likely to become even more important under climate change. However, having the capacity to readily import commodities is of no use if all of the potential exporters have banned exports! So such infrastructure must be accompanied by a set of market policies—both domestic and international, which emphasize flexibility. Unfortunately, international trade negotiations under the auspices of the World Trade Organization (WTO) remain unfinished, as of the time of this writing, and further reductions in agricultural support have been resisted by many countries. However, it is important to point out that, from the viewpoint of adaptation, what is needed first and foremost is not a reduction in average subsidy levels, but rather guarantees that existing policies will not be manipulated to insulate domestic markets. This is a more modest and potentially achievable goal for international trade negotiators to pursue in the future.

As noted earlier, we expect that basic climate information and weather forecasts will become increasingly valuable in the future. However, good weather forecasting is not possible absent reliable observations of historical weather patterns and the status of long term, reliable weather data in many developing countries is abysmal. For example, the Global Yield Gap Atlas (<http://www.yieldgap.org/>) reports less than 50 weather stations in all of West and East Africa with at least 20 years of weather data at the daily time step and of adequate quality for analysis of crop yield impacts. This information is a critical public good that deserves stronger support in the future. It will also be an important input into the development of viable weather index insurance, which will be important in those cases where agricultural producers do not have the capacity to adapt to climate change. While the record to date has been mixed, it is clear that the value of successfully implementing such insurance products will become increasingly important in the future.

Climate information is not the only type of geospatial data that is lacking in many developing countries. Improved information and analytical tools to inform public and private decision making about the land resources are woefully lacking over much of the world. To an outsider, it seems that such information should be easy to obtain. After all, we live in a world of “big data” with satellites

monitoring the Earth's entire surface with high frequency, high-performance computers crunching these numbers and Google Earth serving up interactive maps. However, when it comes to usable data for decision making and policy analysis, the situation is nothing short of embarrassing.<sup>7</sup> The latest peer-reviewed, gridded dataset for global cropland area and yields by 175 UN Food and Agriculture Organization (FAO) crops (something that cannot yet be measured accurately from space) is for the year 2000 (Monfreda et al., 2008) and this is not compatible with the latest peer-reviewed global dataset for irrigated areas and yields, which is also for the year 2000 (Portmann et al., 2010). In India, competing estimates of the extent of irrigated agriculture vary from 62 to 113 million hectares (Hertel and Villoria, 2014). As a consequence of this lack of high quality, interoperable information about the world's land resources and related public goods, it is extremely difficult for decision makers in developing countries to make intelligent decisions about any aspect of land use—whether it is the appropriate price to charge for land leased to large corporations, where to make climate adaptation investments, or assessment of the pros and cons of engaging in payments for environmental services. Information is indeed the ultimate public good and this is an area where additional investment would pay some of the largest dividends—particularly for the poorest countries of the world.

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## Notes

1. Apart from land conversion and nitrous oxide emissions from fertilizer use, the authors do not incorporate other crop-based emissions such as methane emissions from paddy rice production.
2. A petagram is equal to 1.0E12 kilograms.

3. The *TIST* project in Kenya has successfully exploited this feature of traditional tenure systems to implement contracts even in the absence of legal property (see [rights.http://www.tist.org/i2/](http://rights.tist.org/i2/)).
4. For an extended discussion see Hertel and Rosch (2010).
5. For more extended discussion, see Hertel and Rosch (2010).
6. For a detailed discussion of these points, the reader is referred to Angelsen's (2013) REDD+ review as well as his companion paper in this special issue.
7. For a review of the state of play for global land use data, see Hertel et al. (2010a).