

LETTER • OPEN ACCESS

Climate adaptation as mitigation: the case of agricultural investments

To cite this article: David B Lobell *et al* 2013 *Environ. Res. Lett.* **8** 015012

View the [article online](#) for updates and enhancements.

You may also like

- [Feasibility assessment of climate change adaptation options across Africa: an evidence-based review](#)
Portia Adade Williams, Nicholas Philip Simpson, Edmond Totin et al.
- [The FAOSTAT database of greenhouse gas emissions from agriculture](#)
Francesco N Tubiello, Mirella Salvatore, Simone Rossi et al.
- [Impact of climate change on carbon emissions in future road design: frost protection of roads in temperate climates](#)
Lisa Tronhuus Hannasvik, Tore Kvande, Rolf André Bohne et al.

Breath Biopsy Conference

Join the conference to explore the **latest challenges** and advances in **breath research**, you could even **present your latest work!**

 5th & 6th November
Online

Register now for free!



-  **Main talks**
-  **Early career sessions**
-  **Posters**

Climate adaptation as mitigation: the case of agricultural investments

David B Lobell¹, Uris Lantz C Baldos² and Thomas W Hertel²

¹ Department of Environmental Earth System Science and Center on Food Security and the Environment, Stanford University, Stanford, CA 94305, USA

² Department of Agricultural Economics and Center for Global Trade Analysis, Purdue University, West Lafayette, IN, USA

E-mail: dlobell@stanford.edu

Received 28 August 2012

Accepted for publication 10 December 2012

Published 12 February 2013


Online at stacks.iop.org/ERL/8/015012

Abstract

Successful adaptation of agriculture to ongoing climate changes would help to maintain productivity growth and thereby reduce pressure to bring new lands into agriculture. In this paper we investigate the potential co-benefits of adaptation in terms of the avoided emissions from land use change. A model of global agricultural trade and land use, called SIMPLE, is utilized to link adaptation investments, yield growth rates, land conversion rates, and land use emissions. A scenario of global adaptation to offset negative yield impacts of temperature and precipitation changes to 2050, which requires a cumulative 225 billion USD of additional investment, results in 61 Mha less conversion of cropland and 15 Gt carbon dioxide equivalent (CO₂e) fewer emissions by 2050. Thus our estimates imply an annual mitigation co-benefit of 0.35 GtCO₂e yr⁻¹ while spending \$15 per tonne CO₂e of avoided emissions. Uncertainty analysis is used to estimate a 5–95% confidence interval around these numbers of 0.25–0.43 Gt and \$11–\$22 per tonne CO₂e. A scenario of adaptation focused only on Sub-Saharan Africa and Latin America, while less costly in aggregate, results in much smaller mitigation potentials and higher per tonne costs. These results indicate that although investing in the least developed areas may be most desirable for the main objectives of adaptation, it has little net effect on mitigation because production gains are offset by greater rates of land clearing in the benefited regions, which are relatively low yielding and land abundant. Adaptation investments in high yielding, land scarce regions such as Asia and North America are more effective for mitigation.

To identify data needs, we conduct a sensitivity analysis using the Morris method (Morris 1991 *Technometrics* **33** 161–74). The three most critical parameters for improving estimates of mitigation potential are (in descending order) the emissions factors for converting land to agriculture, the price elasticity of land supply with respect to land rents, and the elasticity of substitution between land and non-land inputs. For assessing the mitigation costs, the elasticity of productivity with respect to investments in research and development is also very important. Overall, this study finds that broad-based efforts to adapt agriculture to climate change have mitigation co-benefits that, even when forced to shoulder the entire expense of adaptation, are inexpensive relative to many activities whose main purpose is mitigation. These results therefore challenge the current approach of most climate financing portfolios, which support adaptation from funds completely separate from—and often much smaller than—mitigation ones.

Keywords: agriculture, climate mitigation, adaptation

 Online supplementary data available from stacks.iop.org/ERL/8/015012/mmedia



Content from this work may be used under the terms of the [Creative Commons Attribution-NonCommercial-ShareAlike 3.0 licence](http://creativecommons.org/licenses/by-nc-sa/3.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

1. Introduction

Climate change mitigation is defined as ‘an anthropogenic intervention to reduce the sources or enhance the sinks

of greenhouse gases' [2]. Climate adaptation, on the other hand, is often defined as 'adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities' [2]. Mitigation and adaptation are most often viewed as two separate but complementary approaches to avoid damages from climate change. Any investment portfolio to reduce impacts should have some component of each, and many integrated assessment studies have evaluated the optimal global mix of mitigation and adaptation efforts [3, 4]. The two are mainly viewed as substitutes for each other, with more investment in mitigation reducing the need for adaptation, and vice versa. As substitutes, mitigation and adaptation are also often in direct competition for a finite pool of resources devoted to climate change (e.g., the Green Climate Fund).

Recently, attention has also been paid to the more direct connections between mitigation and adaptation [5]. These connections include possible synergies, such as when sequestering carbon in soils also improves their ability to retain moisture and cope with drought, as well as conflicts or 'disharmonies' [6], such as when increased irrigation pumping or indoor air conditioning to deal with heat waves leads to additional energy use and associated greenhouse gas (GHG) emissions. Synergies are attractive because they offer the chance to make more efficient use of limited resources for reducing climate damage. However, quantitative measures of the effects of different activities on both mitigation and adaptation remain lacking, and without these measures it is very difficult to identify the true potential and attractiveness of specific activities.

In this paper, we focus on an activity that has not yet received attention in the literature on harmonizing climate adaptation and mitigation: investing in agricultural research and development (R&D) for adaptation to climate change. In most discussions, investments in agricultural adaptations are viewed exclusively within the realm of adaptation, and they are accordingly funded out of the adaptation portions of climate funds (which are typically much smaller than mitigation portions). However, the goal of adaptation activities, such as adoption of drought tolerant seeds or improved irrigation, is often to maintain productivity in agriculture, which in turn is an important determinant of overall land use decisions. Given that land use change remains an important source of GHG emissions, investments in agriculture have potential impacts on mitigation efforts. A recent study [7], for example, estimated that global investments in agriculture over the past 50 years helped to avoid emissions at an effective rate of \$4–\$9 per tonne CO₂e—a figure which is competitive with many current mitigation activities.

The goal of this paper is to quantify the potential effects of future adaptation investments on global GHG emissions, using a model that represents the dynamics of food production, consumption, and land use change. Section 2 provides a brief background on the links between agricultural productivity, land use change, and GHG emissions. Section 3 describes the model used in this study and the experimental

design. Section 4 presents the main results along with uncertainty and sensitivity analysis, and section 5 discusses conclusions and implications. Given the many links that connect agricultural investments to GHG emissions, and the limited knowledge on each of these links, we do not view estimates from this or any other study as definitive. Rather, the goal is to determine plausible expected values and ranges of uncertainties and, perhaps most usefully, to identify with sensitivity analysis the key model parameters to resolve in order to improve future estimates. Our conclusions therefore include suggestions on where to focus future data collection and modeling efforts on this topic.

2. Background on agricultural productivity and land use change emissions

The link between agricultural productivity and land use change was most famously emphasized by Norman Borlaug, the so-called 'father of the Green Revolution', who argued that (i) people need to eat, (ii) the amount of food available is the product of total cropland area and the yield per hectare, and therefore (iii) yield gains reduce the amount of total cropland area needed, and thus help to avoid global cropland expansion. This 'Borlaug Hypothesis' has been widely discussed in the literature, much of which points to factors that modify the link between productivity and land use. In particular, the local land saving effect of technology for higher yields is strongest when it is adopted over broad areas, in areas that do not have large and mobile labor supplies, and for items which have price-inelastic demand (i.e., price reductions do not spur large increases in demand) [8].

In contrast, higher yields can sometimes increase local land use change, by making production and expansion more profitable. This so-called 'Jevons' paradox' is especially likely if yield gains are only realized locally, if local suppliers are connected to global markets, and if it occurs for commodities for which demand is very price elastic [8]. However, even in these situations, local increases in land expansion are likely to be offset by reductions in area expansion in the rest of the world [9].

Although often mischaracterized, the 'Borlaug hypothesis' does not imply that higher yields are sufficient in themselves to avoid cropland expansion over time, either at the local or global scale. Nor does it imply that individual countries with higher yield growth should have less land use change, given the reality of globally integrated markets. Therefore, the 'Borlaug hypothesis' is most fairly evaluated at global scale rather than at country scale. Moreover, only by comparing observed cropland areas to a counterfactual scenario of no yield increase, rather than to cropland areas at previous points in time (when populations and incomes were different), is it possible to isolate the impact of technological change on land use. In summary, a lack of correlation between yield growth and area expansion across space [10] or simultaneous increases in global yields and cropland area do not refute the basic concept that higher yields are land saving.

Past research therefore points to two clear needs for analysis of agricultural productivity and land use. First is

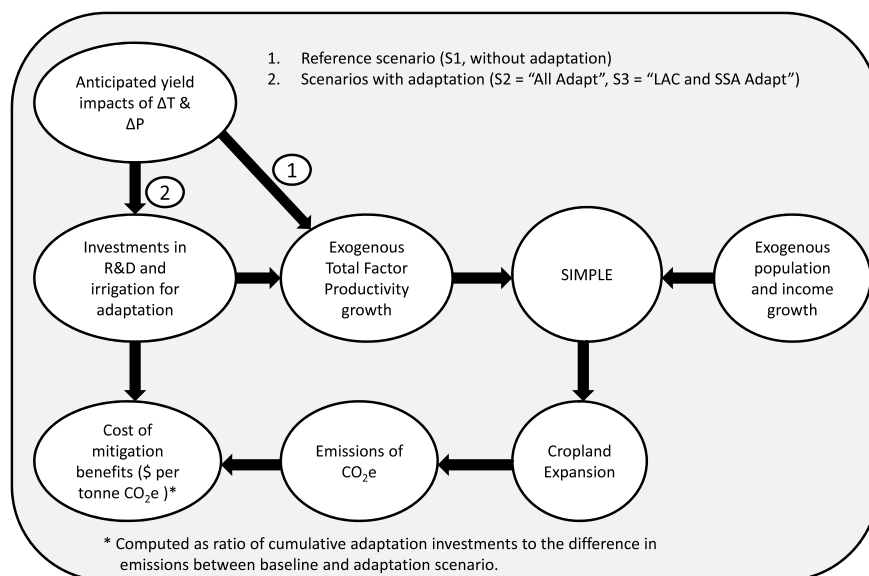


Figure 1. Overview of study approach. The simplified international model of agricultural prices landuse and the environment (SIMPLE) is used to simulate changes in cropland expansion and emissions of carbon dioxide equivalents for different scenarios of adaptation. The costs of each adaptation scenario are divided by the total effect on emissions to compute the per tonne costs of mitigation. The model is applied repeatedly for different parameter values to conduct uncertainty and sensitivity analysis.

to ensure that studies look beyond local scales to consider global-scale dynamics in agricultural trade and land use. Second is to identify a credible counterfactual scenario. The simplest approach is to specify different scenarios of what total food consumption would have been in the absence of yield growth, and then to compute associated cropland area requirements [7]. A more involved approach specifies population and income growth, as well as various parameters that define the responsiveness (or elasticity) of supply and demand to price and income changes, and then uses a partial or general equilibrium model to endogenously determine how food prices and land use patterns change. For example, Evenson *et al* [11] used IFPRI's partial equilibrium IMPACT model to estimate the land saving effect of investments in the Green Revolution, and Stevenson *et al* [9] used the general equilibrium GTAP model to revisit this question as well as explore the effects of recent yield increases in Brazilian soybean and Indonesian oil palm.

Translating land use change to estimates of GHG emissions requires an additional layer of assumptions about the emissions factors associated with land conversions. Land use change has long been understood as an important contributor to global GHG emissions [12], but geographically explicit estimates of how much GHG is released upon conversion of specific land areas continues to be refined. In estimating GHG emissions for historical scenarios, for example, Burney *et al* [7] calculated expansion into each biome by assuming historical patterns of clearing by biome were followed in the counterfactuals, and then used biome-specific emissions factors.

In summary, there is strong evidence that cropland expansion is a source of GHG emissions, and there are strong arguments (albeit less direct evidence) that raising global average productivity leads to smaller rates of global cropland

conversion. However, these two statements do not necessarily guarantee a net reduction of GHG emissions from higher yield growth, as a net global reduction in cropland area could result from decreases in carbon poor areas and expansion in carbon rich areas (e.g., tropical forests or peatlands). Thus, the spatial pattern of yield improvements and associated land use changes are also of concern.

3. Methods

3.1. Overview

Figure 1 presents an overview of the study approach. We begin by defining a scenario of agricultural technological change for the year 2050, where technology change here is defined as growth in total factor productivity (TFP), i.e. an index of outputs attainable from a given amount of total inputs. Different scenarios of TFP are used to reflect different scenarios of adaptation investment, as described in more detail below. The TFP scenario, along with scenarios of population and income changes, are then fed into a partial equilibrium model (described in section 3.2), which calculates the resulting world crop prices and cropland areas by region. Expansion of cropland area in each region is then multiplied by a GHG emission factor to compute total CO₂e emissions from cropland expansion, while area contraction is multiplied by a region-specific sequestration factor. Finally, the total amount of investment required to achieve the TFP scenario is computed. By comparing scenarios with and without adaptation investment, we then compute the total CO₂e emissions and agricultural investment changes associated with adaptation. From these we can calculate the ratio of investment to mitigation, or the dollars per ton of CO₂e avoided. It is important to bear in mind that computing the

Table 1. Key growth rates from 2006 to 2050 (compounded annual percentage growth rate) used in SIMPLE.

Income regions	Population	Per capita income	TFP	
			Livestock	Processed food
Upper high	0.33	1.22	0.4	
Lower high	1.02	2.17	0.4	
Upper middle	0.53	2.74	0.8	0.65
Lower middle	0.22	5.03	2.2	
Low	1.17	4.62	0.3	
Sources of data	[14]	[15]	[19]	[20]
Geographic regions	Built-up land expansion	Climate change TFP shocks	Biofuel use	TFP crops
East Asia and Pacific	2.37	−0.41		
Europe and Central Asia	1.3	0.04		
Latin America and Caribbean	1.99	−0.17		
Middle East and North Africa	2.55	−0.32		
North America	1.91	−0.15		
South Asia	3.32	−0.73		
Sub-Saharan Africa	3.76	−0.16		
Global			5.4	0.83
Sources of data	[17]	[25]	[16]	[18]

mitigation costs in this way attributes all of the expenditure to mitigation, whereas the primary motivation for this investment is adaptation.

Given the many parameters involved in this process, an essential part of this study is uncertainty and sensitivity analysis. The entire process above is therefore repeated a large number of times, with different parameter values chosen each time based on standard sensitivity analysis techniques (described below). From this analysis we summarize the distribution of plausible outcomes as well as the relative importance of different parameters in overall uncertainty—information which is useful to guide future investments in data for decision making with respect to climate policy.

3.2. Model description

We use the ‘SIMPLE’ model (simplified international model of agricultural prices land use and the environment) for our simulations (described in the supplementary information (available at stacks.iop.org/ERL/8/015012/mmedia) and more fully in [13]). As the name suggests, this economic model is designed to be as simple as possible, while retaining sufficient region and sector richness to reflect global changes in food demand, crop production and cropland use. Crops are produced in seven geographic regions, which is clearly a simplification of real-world heterogeneity but captures broad-scale regional disparities. Crop supply is increased by producing at the extensive margin—via expansion of croplands—and at the intensive margin in the form of increased crop yields. The demand for crop output is derived from the global feedstock demand by the world biofuel industry, direct food consumption and indirect consumption as livestock feed or raw inputs into the processed food sector. Demand for each of these end-uses is determined by changes in income, prices, and population. Consumption is defined over five regions, differentiated by per capita income level. These regional distinctions capture the differential impact of

income growth on food demand as income levels rise, and the shifts in crop production and cropland use across geographic regions. In this long run model, global crop production is required to equal global demand for crops and there is a single world price for this aggregated crop product.

Since our goal is to project forward for more than 40 years, we first validate the model by backcasting from 2006 to 1961, a period over which agricultural output rose by nearly 200%, while cropland area expanded by just 16%. Using only population, income and total factor productivity (TFP) in crops, livestock and food processing, the model is able to endogenously capture these broad developments in global agriculture over this period—in particular the dominant expansion at the intensive margin (for details, see [13]).

Forward looking model simulations from 2006 to 2050 require baseline assumptions on growth rates of key drivers of global cropland use over this future period. These are reported in table 1. Population growth rates are taken from the UN World Population Prospects [14] using the ‘Medium’ fertility scenario. These rates vary greatly across regions. The highest population growth rate is in the poorest countries (driven by Africa), while the lowest growth rates are in the highest income region and the low middle income region (dominated by China which has sharply limited population growth through its one-child policy). Regional income growth rates are based on extension of the projections from the USDA ERS International Macroeconomic Data Set [15]. These growth rates tend to decline with rising income levels. Future growth in biofuel production is a global-scale shock to crop demand and is based on the IEA’s World Energy Outlook 2010 [16] under their ‘current policies’ scenario. The encroachment of built lands into existing croplands is also considered using built-up land expansion rates from [17]. Technical changes in the crop, livestock and processed food sectors are modeled via changes in TFP. TFP growth rates for these sectors are taken from [18–20], respectively.

In the sensitivity analysis, we vary 15 key global model parameters which govern crop production, commodity

Table 2. Key model parameters in SIMPLE, showing mean values and ranges use in uncertainty and sensitivity analysis. (Note: w.r.t. = with respect to.)

Parameters	Description	Mean	Max	Min	Sources of data used in computing model parameters
ELANDW	Elasticity of land supply w.r.t. land rents	0.11	0.14	0.08	[41, 42]
ENLANDW	Elasticity of non-land supply w.r.t. non-land rents	1.34	1.74	0.94	[43]
LCFURBW	Conversion factor of urban land to cropland	0.23	0.30	0.16	[44–46]
NCRP2CRPW	Emission factors (MgCO ₂ eq/ha) non-crop to crop conversion	286.97	373.06	200.88	[22]
CRP2NCRPW	Emission factors (MgCO ₂ eq/ha) crop to non-crop conversion	−142.19	−99.53	−184.84	[22]
ECROPW	Elasticity of substitution in production of crops	0.55	0.72	0.39	[43]
EINVW	Elasticity of TFP w.r.t. agricultural investments	0.30	0.38	0.21	[27]
EIY ('Crops', 'Intercept')	Elasticity of crop demand w.r.t. income (intercept of line of elasticity versus income)	0.88	0.93	0.83	[21]
EIY ('Livestock', 'Intercept')	Elasticity of livestock demand w.r.t. income	1.05	1.09	1.01	[21]
EIY ('Proc.Food', 'Intercept')	Elasticity of processed food demand w.r.t. income	1.20	1.24	1.15	[21]
EIY ('Non.Food', 'Intercept')	Elasticity of non-food demand w.r.t. income	1.56	1.65	1.46	[21]
EIP ('Crops', 'Intercept')	Elasticity of crop demand w.r.t. price	−0.74	−0.71	−0.77	[21]
EIP ('Livestock', 'Intercept')	Elasticity of livestock demand w.r.t. price	−0.83	−0.80	−0.85	[21]
EIP ('Proc.Food', 'Intercept')	Elasticity of processed food demand w.r.t. price	−1.17	−1.13	−1.21	[21]
EIP ('Non.Food', 'Intercept')	Elasticity of non-food demand w.r.t. price	−1.14	−1.07	−1.21	[21]

demand and GHG emissions from cropland changes (table 2). Crop production parameters include the elasticity of substitution between land and non-land inputs, as well as the price elasticity of land and non-land input supplies. Selected global parameters are scaled in each region to reflect regional differences in land availability (table S1). Demand for each commodity is governed by income and price elasticities which decline with growth in per capita income. This relationship is directly incorporated in the model using parameters from linear regressions of the elasticity estimates of Muhammed *et al* [21] on per capita income.

Changes in cropland cover simulated in SIMPLE are translated into direct GHG emissions or sequestration using global emission factors for non-cropland to cropland conversion and for cropland to non-cropland conversion. The emission factors are taken from [22], although other potential sources of such data also exist [23]. Other model parameters include the global conversion factor from urban land to croplands and the elasticity of yields with respect to investments in agriculture, which is used to estimate the cost of achieving a given change in TFP.

A key feature of SIMPLE is its computational simplicity, which allows the model to be run a large number of times to fully explore the parameter space. This is analogous to the use of simplified integrated assessment models such as

DICE [4], as well as intermediate complexity models in climate science [24], which reproduce the broad behavior of more complex models but sacrifice detail in order to allow a much larger number of simulations for activities such as sensitivity analysis.

3.3. Experimental design

Three separate scenarios are simulated in order to investigate the effects of adaptation on emissions:

- (1) A reference scenario (S1) in which the full effects of temperature and precipitation changes on agriculture are evidenced. This is the 'no planned adaptation' case—although the economic system does permit adjustment to these shocks, and the shocks themselves account for some autonomous biophysical adaptation. To represent climate impacts, we take the baseline values for TFP growth in SIMPLE and add the annualized impacts of climate change estimated by Müller *et al* [25] for the 2010 World Development Report [26]. Müller *et al* report impacts by mid-century, both with and without effects of CO₂ fertilization. Here we use the impacts without CO₂ effects, which reflect only the effects of changes in temperature and precipitation. Importantly, the modeling approach

used by Müller *et al* accounts for autonomous adaptations such as switching among existing crops and varieties. It is therefore appropriate to assume that planned adaptations, such as investment in new research, are needed to adapt to the impacts used here. Table 1 presents the impacts of projected 2050 temperature and precipitation changes on TFP, which are negative in all regions except Europe. Although we rely on a single study of climate impacts, these estimates are broadly consistent with other global assessments in the literature, which anticipate negative impacts in most developing countries [27, 28].

- (2) A scenario in which all regions fully adapt to climate change (S2), meaning that they restore their TFP to the levels that would have prevailed without temperature and precipitation changes. Europe, which is the lone region in [25] to benefit from climate changes to 2050, is not adjusted under this scenario, as no planned adaptation is required. Note that by ignoring the benefits of CO₂, we focus here on adaptation investments aimed at avoiding the negative effects of warming and precipitation changes, and assume the levels of investment needed for this goal are not affected by CO₂ levels. This assumption ignores potentially important issues such as interactions between high temperatures and CO₂.
- (3) A scenario in which only Latin American and the Caribbean (LAC) and Sub-Saharan Africa (SSA) adapt to climate change (S3). Again, adaptation is defined in this scenario as restoring TFP to pre-impact levels. This scenario is intended to probe the potential importance of regional disparities in adaptation investment, given that the 'land saving' effect of productivity gains depends on where those gains are realized (see section 2). LAC and SSA have the highest land supply elasticities of all regions (table S1), as well as relatively low yields, both of which are conditions that reduce the land saving effect. Scenario S3 is therefore intended to represent a lower bound scenario for the mitigation benefits of adaptation. It will be contrasted with the broad-based adaptation scenario of S2.

3.4. Calculating costs and mitigation benefits of adaptation

For scenarios S2 and S3, the total amount of investment needed to fully adapt to climate change (i.e., restore TFP to levels without climate change) in each region is calculated by assuming an elasticity of TFP to investment of 0.3. That is, a 10% increase in agricultural investment is assumed to result in a 3% increase in TFP. This value is taken from Nelson *et al* [27], where it is based on expert estimates on effects of spending on R&D. However, most econometric analyses in the literature give quite similar values for this key parameter [29]. We also vary this value by $\pm 30\%$ in sensitivity analysis, as described below.

Importantly, in light of the substantial lags between research expenditures and adoption of new technologies [30] we assume that R&D investment must be sustained for

20 years in order to result in permanent effects on TFP. Specifically, total investment in a region is calculated as:

$$\text{Total investment} = \text{AGINV}_0 \left(1 + \frac{\text{TFP}_{\text{REF}} - \text{TFP}_{\text{CC}}}{\text{EIN VW}} \right) \quad (1)$$

where AGINV₀ is the current annual public and private investment in agricultural R&D in a given region, obtained from Pardey *et al* [31], (TFP_{REF} – TFP_{CC}) corresponds to the TFP impact of climate change in the absence of adaptation, and EIN VW is the elasticity of TFP with respect to R&D investment. By focusing on R&D investments alone, we do not explicitly consider other ancillary public and private investments that are likely needed for adaptation, such as irrigation infrastructure or roads [27]. Implicitly, we therefore assume that these other investments have similar marginal returns as R&D over the scales considered in this study. Strictly speaking, however, our results should be interpreted as the mitigation benefits of investment in R&D, rather than a broader suite of adaptation investment.

3.5. Uncertainty and sensitivity analysis

A common shortcoming of models that forecast agriculture and land use change is a lack of rigorous uncertainty and sensitivity analysis (UA and SA, respectively). For many models, the large number of parameters and computational expense of each model run make it prohibitive to systematically explore parameter space. Simple screening techniques are sometimes used, in which parameters are changed one-at-a-time while all others are held fixed at baseline values, but these techniques have well known limits when applied to models with many interacting and nonlinear equations [32].

Due to its parsimony, SIMPLE affords an opportunity to apply more complete UA and SA techniques. For UA, we reran SIMPLE 1000 times, each time with model parameters randomly chosen from predefined distributions. A total of 15 model parameters were varied, with the range of values and their sources listed in table 2, and a triangular distribution assumed for each parameter. Rather than vary regional parameters independently, we defined a global value for each set of parameters, with regional values defined relative to the global value (table S1). This is consistent with the sourcing of our parameter estimates, which are typically geared around one point estimate which is subsequently differentiated by region according to income (price and income elasticities) or land endowment (land supply elasticities). Thus, in each run of the model, all regional values were moved up or down together based on the global value.

For SA we employ the Morris method [1], which is a global one-at-a-time SA approach detailed in the supplementary information (available at stacks.iop.org/ERL/8/015012/mmedia) [32]. For presentation, we divide all importance measures from the Morris method by the maximum value to produce a normalized importance measure that ranges from 0 to 1 for each model output.

The UA and SA focus on the key parameters of the model, but not on the input scenarios of population, income

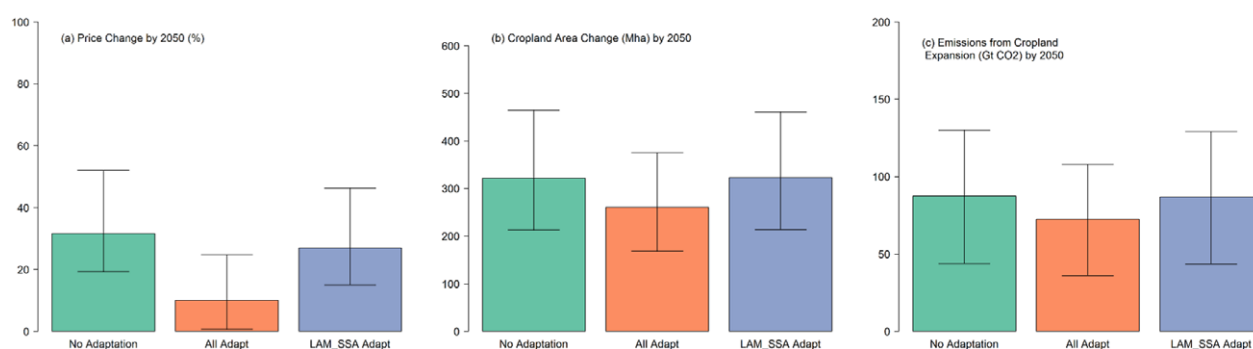


Figure 2. Simulated changes for 2050 relative to 2006 for (a) crop prices, (b) cropland area, and (c) land use emissions. Bars show median values across all simulations, and error bars indicate 5th–95th percentile confidence interval.

Table 3. Change in global outcome variables for each adaptation scenario: 2006–2050. Values are medians across all simulations.

Global variables	Units	Scenarios			Effects of adaptation	
		S1	S2	S3	S2–S1	S3–S1
Crop price		32	10	27		
Crop production		96	102	97		
Cropland	%	23	18	23		
Crop yields		60	72	61		
Change in cropland cover	Million ha.	322	261	323	–61	+1
Land use change emissions	Billion tonne CO ₂ eq.	87	72	87	–14.8	–0.4
Ag. R&D investments for adaptation	Billion 2000 USD	0	225	21		
Cost effectiveness of mitigation	USD per tonne CO ₂ eq.	N/A	15.3	54.5		

and climate change impacts. All results should therefore be considered conditional on these particular scenarios, although we anticipate that most results are robust across various scenarios. An exception is the total investment costs and mitigation potential of adaptation, which depends on the climate change impacts. Results for scenarios with higher or lower climate impacts resulted in proportionally higher or lower investment costs and mitigation potential (not shown). However, since the mitigation cost per tonne CO₂e is calculated as the ratio of these two values, it was unaffected by changing the climate impact scenario.

4. Results and discussion

4.1. Estimates and uncertainties

In the reference scenario (S1), in which the effects of climate change are not avoided with adaptation (and we ignore the benefits of CO₂ fertilization), global food prices increase by 32% by 2050, compared to 2006 (table 3, figure 2(a)). Global crop production increases by 96%, which comes from a 23% expansion of cropland area and 60% increase in crop yields (table 3). The majority of cropland expansion occurs in Latin America and the Caribbean (LAC) and Sub-Saharan Africa (SSA), because these areas are prescribed to have the most elastic land supply response to prices (higher values for ELAND) (table S1 available at stacks.iop.org/ERL/8/015012/mmedia). Compared to the 45 year historical period, this is a much slower growth rate in total output, reflecting the slower rate of population and income growth and the declining

income elasticities of demand for food as incomes rise. The doubling of global production and 60% yield increase is consistent with other recent projections of crop demand and supply in 2050 [33, 34].

It is also notable that relatively more of the production growth comes from cropland area expansion (23% versus only about 8% over the historical period). This reflects in part the lower yield growth owing to climate change (compare columns S1 and S2 in table 3). When compared to the IFPRI baseline with climate change impacts included (113%–194%, depending on crop type and climate model used), our price increases are much more modest. This is a function of many factors, but foremost among these are the smaller climate change impacts from Müller *et al* [25] and the larger demand and supply elasticities in our model. Hertel [35] suggests that the IFPRI elasticities are not truly long run, and argues that this is an important reason for the very strong price effects emerging from that model.

All three scenarios result in cropland expansion and associated GHG emissions, with a total of 87 Gt CO₂e emitted from conversion of 322 Mha in the reference scenario (table 3). The 5–95% confidence intervals around these numbers are 44–130 Gt CO₂e and 213–464 Mha, respectively (figure 2). These uncertainties reflect the imperfect knowledge of all of the economic and biophysical parameters shown in table 2. The fact that emission outcomes span a larger range than land expansion outcomes (factor of three compared to a factor of two) indicates the effect of additional uncertainty that enters when translating land conversion rates into emission rates (i.e. NCRP2CRPW and CRP2NCRPW in table 2).

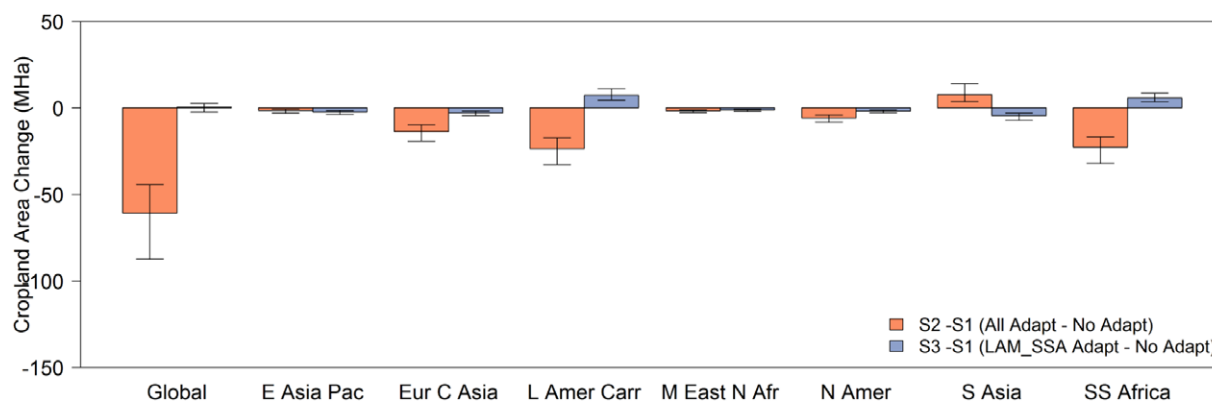


Figure 3. Simulated impact of adaptation on global and regional cropland areas in 2050, for two adaptation scenarios.

As expected, a scenario of adaptation in those regions of the world where climate impacts are negative (S2) results in a diminution of crop prices and cropland expansion, when compared to S1. Price increases of 32% in S1 are cut by two-thirds to 10% in S2, and 61 Mha of land are spared from conversion to agriculture (a reduction of roughly 20% from S1). Associated with this reduction in cropland expansion is a net decrease in cumulative emissions of 15 GtCO₂e (0.34 Gt per year), with a 5–95% confidence interval of 11–19 Gt CO₂e (0.25–0.43 Gt per year).

A scenario of adaptation focused only in LAC and SSA (S3) helps to reduce crop prices and sustain higher levels of consumption than in S1. However, in contrast to S2, S3 shows very small effects on global cropland area or GHG emissions compared to no adaptation. Scenario S3 does result in lower cropland area and emissions in some regions relative to S1, but these gains are offset by *increases* in area and emissions in LAC and SSA relative to S1 (figure 3).

These results emphasize the importance of regional disparities in land supply elasticities and average yields. Because LAC and SSA have relatively high elasticities (ELAND), improving economic returns to cropping, in these regions alone, provides a strong incentive to clear more land. Moreover, because these regions are low yielding relative to others, it takes more land to produce the same amount of crop output. This result is consistent with the observation that carbon loss per ton of food produced on each hectare of new land is greatest in tropical regions [36]. Emission factors per ha (NCRP2CRP) in LAC and SSA are slightly higher and lower, respectively, than the global average, so additional emissions in these areas roughly equals the emissions reductions in other regions (with a slight net reduction in the median case).

The median estimated cumulative costs associated with adaptation in the simulations are \$225 billion USD for S2 and \$21 billion USD when adaptation is focused exclusively on LAC and SSA (S3). The ratio of investment costs to total emissions savings for each scenario indicates a median mitigation cost of \$15.20 USD per tonne CO₂e in (S2), and more than three times that amount (\$55.20) for S3. The distributions of these values across all simulations are skewed to the right (figure 4), with a 5–95% confidence interval of

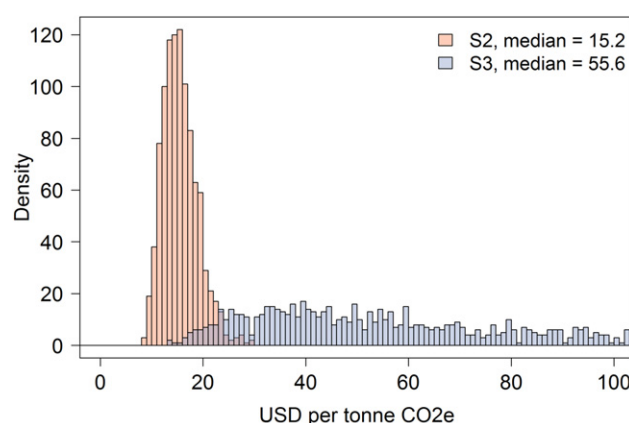


Figure 4. The distribution of simulated per tonne mitigation costs resulting from two scenarios of adaptation, across all combinations of model parameters.

\$11–\$22 for S2 and \$0–\$320 for S3. This skewness reflects the fact that the ratio can grow very large if the emissions savings are small, as occurs in S3 under many possible parameter combinations.

Are mitigation benefits of roughly \$15 USD per tonne CO₂e in scenario S2, with a total abatement of 15 Gt CO₂e over 2006–2050, large enough to be economically relevant within the current policy environment? For comparison, market prices for carbon on the European Energy Exchange have fluctuated between \$10–\$20 USD per tonne CO₂e in the period since 2010 (www.eex.com/en/MarketData). As of 1 July 2012, Australia implemented a carbon tax of slightly more than \$24 USD per tonne CO₂e (www.cleanenergyfuture.gov.au/). Most estimates of the likely future marginal cost of emissions reductions required to keep atmospheric CO₂e at or below 550 ppm are well above \$15 [37, 38]. On a mitigation cost basis alone, investing in agricultural adaptation therefore appears to be a reasonable mitigation strategy.

The abatement potential, which is determined here by the total amount of climate impacts to be avoided with adaptation, is roughly 0.35 Gt CO₂e per year. This is at the low end of various potential mitigation activities, similar to activities such as improved waste management or increased co-firing of biomass [37, 39]. Of course, the mitigation potential of

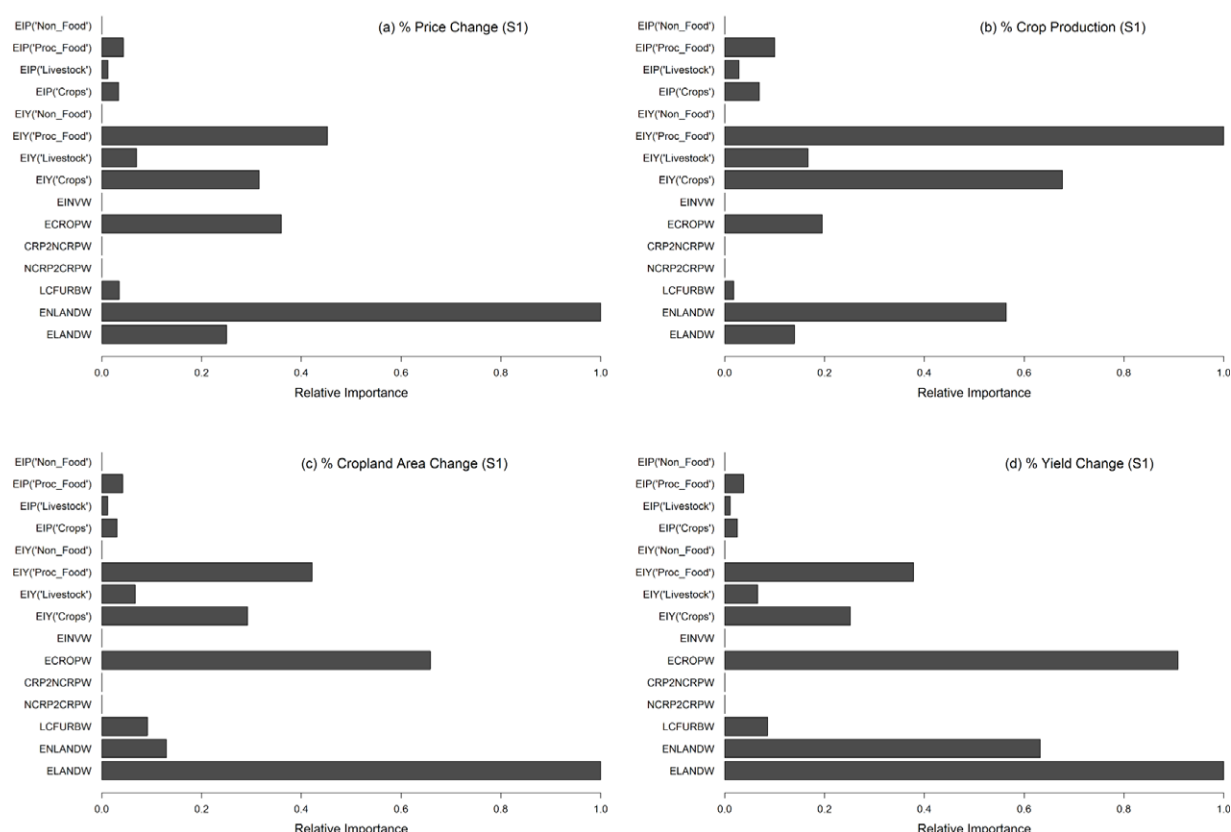


Figure 5. Sensitivity analysis results for four model outcomes in the reference scenario. Bars show the relative importance of each parameter based on analysis with the Morris method.

agricultural investments defined more broadly (i.e. not only those focused on adapting to climate change) is substantially higher [7, 40].

4.2. Sensitivity analysis

Given the many uncertainties involved in estimating the quantities presented in section 4.1, here we evaluate which parameters contribute most to uncertainty and therefore deserve most scrutiny for future refinement. We begin with an analysis of the results in the reference scenario (S1), which summarize the behavior of the economic model (figure 5). The most important parameter for projecting price changes by 2050 (taking population and income levels as given) is the globally averaged price elasticity of non-land inputs (ENLANDW, e.g., fertilizer, irrigation capital, hired labor). If these inputs are very responsive to prices, then less of a price increase is needed to spur production increases. Indeed, as the price elasticity of non-land inputs approaches infinity (i.e., these variable input prices are dictated entirely by the nonfarm economy) then the output supply response for crops is determined entirely by the potential for substituting these inputs for land (ECROPW) since land is the relatively scarce factor of production. In addition, the ability to expand land area in response to higher prices (ELANDW) is also a key factor in determining the crop price change over the baseline.

For changes in total production (figure 5(b)), the income elasticities of demand play a larger role, and ENLANDW

remains important because it influences price increases, which in turn curbs consumption. Cropland area and yields (figures 5(c) and (d)) are sensitive to similar factors, which is unsurprising since these represent two complementary margins on which production can be increased. The two most important parameters for both area and yield changes are ELANDW and the elasticity of substitution between land and non-land inputs (ECROPW).

Turning to the outcomes of main interest in this paper, the amount of cropland expansion avoided by adaptation (figure 6(a)) is unsurprisingly sensitive to the same factors that determine overall cropland area expansion in the reference scenario. Emission savings associated with the avoided expansion is most sensitive to NCRP2CRPW, the parameter that prescribes the amount of CO₂e emitted when converting one hectare of cropland in each region (figure 6(b)), with parameters affecting total amount of land conversion of secondary importance, but still significant. Finally, the cost of emissions is roughly equally sensitive to the emissions factors and EINW, the elasticity of productivity to investments in agriculture (figure 6(c))—these being the ‘front line’ parameters involved in the determination of the co-benefits and costs, respectively, of adaptation.

Overall, the sensitivity analysis results demonstrate that both demand and supply side parameters influence the trajectory of future production and land use, as well as the benefits of agricultural investments for mitigation. However, the parameters whose current level of uncertainty most

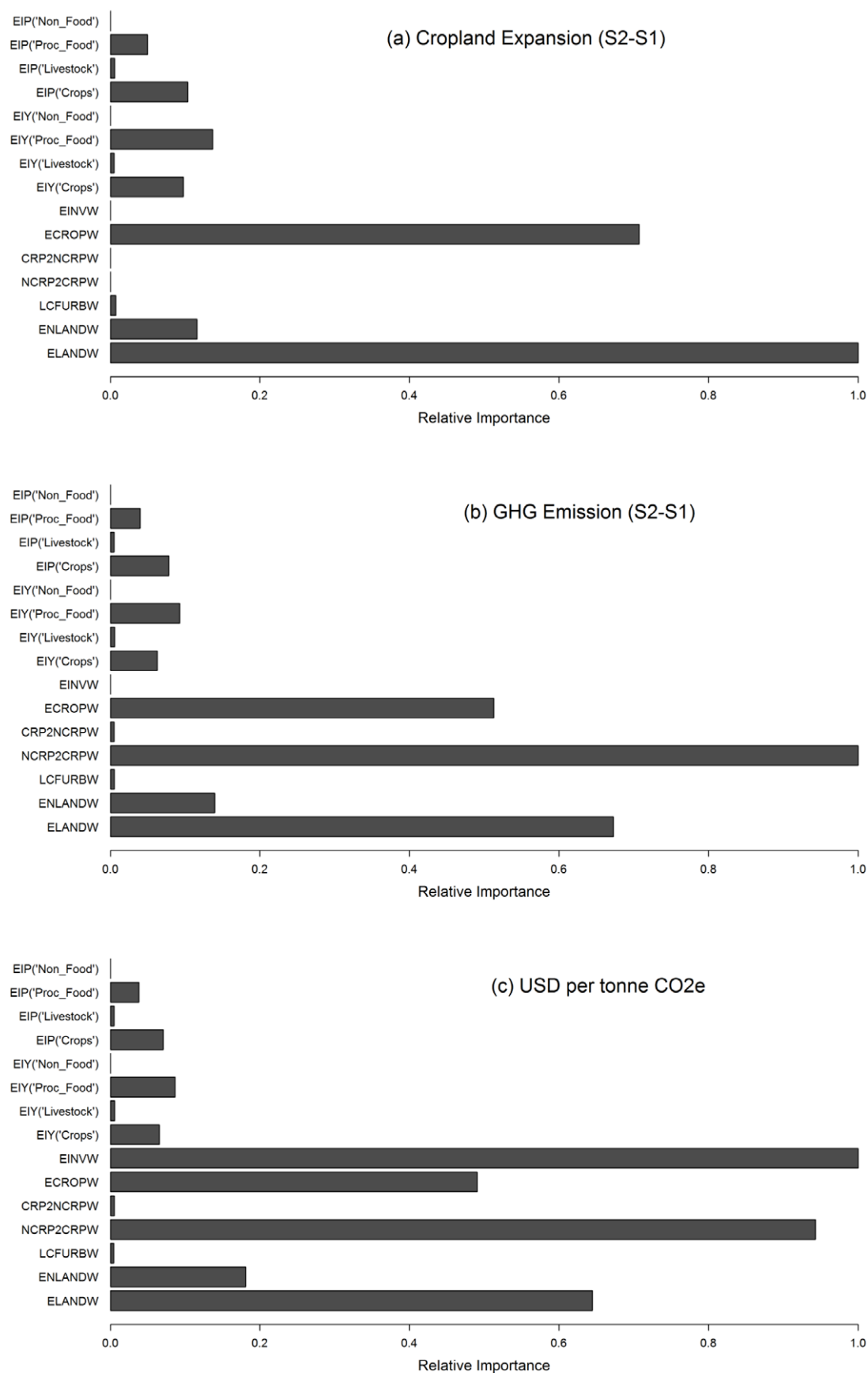


Figure 6. Sensitivity analysis results for the effect of adaptation in the 'All adapt' scenario (S2) on (a) cropland area, (b) greenhouse gas emissions, and (c) mitigation cost per tonne CO₂e. Bars show the relative importance of each parameter based on analysis with the Morris Method.

influence the key results are the responsiveness of productivity to investment, the amount of CO₂e lost upon conversion of non-cropland into cropland, the price elasticity of land supply, and the elasticity of substitution of non-land for land inputs in crop production.

5. Conclusions

Three outcomes of this study appear worthy of emphasis. First, the mitigation co-benefits of investing in agricultural adaptation appear substantial. The total mitigation potential (0.35 Gt CO₂e per year) and cost (\$15 per tonne CO₂e) of broad-based investments in adaptation are themselves attractive enough to rival many other mitigation activities, notwithstanding the more direct economic benefits for consumers that come from higher productivity and lower prices for food. Indeed, these co-benefits would themselves be sufficient to justify widespread agricultural adaptation investments given current carbon prices in, for instance, Europe and Australia.

Second, although focused adaptation efforts in regions such as Africa may be justified from the standpoint of improving food security, improvements in these areas are relatively ineffective from a mitigation standpoint. Indeed, avoiding negative impacts of climate change in South and East Asia, where current yields are higher and potential supply of new croplands is smaller, are more important for maintaining global productivity and stemming cropland expansion.

Third, key parameters needed to improve upon the estimates here include those related to responsiveness of land supply to food prices, the potential for intensification of crop production, the responsiveness of productivity to research investments, and the emission intensity of converting native lands to cropland. Additional datasets and analyses related to these factors appear more useful, for example, than efforts to determine demand responses to incomes or prices. Despite these remaining needs, however, uncertainty analysis indicates a low (5%) chance that mitigation via global agricultural investment will exceed a cost of \$22 per tonne CO₂e. We therefore conclude that investments in climate adaptation in agriculture represent a good opportunity for climate mitigation, adding to the more widely acknowledged benefits of adaptation for poverty reduction and enhanced food security.

Acknowledgments

The authors thank Gerald Nelson for valuable input and two reviewers for helpful comments. TWH acknowledges support from the DOE, Office of Science, Office of Biological and Environmental Research, Integrated Assessment Research Program, Grant No. DE-SC005171.

References

- [1] Morris M D 1991 Factorial sampling plans for preliminary computational experiments *Technometrics* **33** 161–74
- [2] IPCC 2001 *Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II, III to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: IPCC)
- [3] Tol R S J 2005 Adaptation and mitigation: trade-offs in substance and methods *Environ. Sci. Policy* **8** 572–8
- [4] Nordhaus W D 1994 *Managing the Global Commons: The Economics of Climate Change* (Cambridge, MA: MIT Press)
- [5] Klein R J T et al 2007 Inter-relationships between adaptation and mitigation *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed M L Parry, O F Canziani, J P Palutikof, P J v d Linden and C E Hanson (Cambridge: Cambridge University Press) pp 745–77
- [6] Moser S 2012 Adaptation, mitigation, and their disharmonious discontents: an essay *Clim. Change* **111** 165–75
- [7] Burney J A, Davis S J and Lobell D B 2010 Greenhouse gas mitigation by agricultural intensification *Proc. Natl Acad. Sci.* **107** 12052
- [8] Angelsen A and Kaimowitz D 2001 *Agricultural Technologies and Tropical Deforestation* (Wallingford: Cabi Publishing)
- [9] Stevenson J, Byerlee D, Villoria N, Kelley T and Maredia M 2012 Agricultural technology, global land use and deforestation: a review *Proc. Natl Acad. Sci.* in revision
- [10] Rudel T K et al 2009 Agricultural intensification and changes in cultivated areas, 1970–2005 *Proc. Natl Acad. Sci.* **106** 20675–80
- [11] Evenson R E and Gollin D 2003 Assessing the impact of the green revolution, 1960 to 2000 *Science* **300** 758–62
- [12] Dixon R K, Solomon A M, Brown S, Houghton R A, Trexler M C and Wisniewski J 1994 Carbon pools and flux of global forest ecosystems *Science* **263** 185–90
- [13] Baldos U and Hertel T W 2012 *SIMPLE: A Simplified International Model of Agricultural Prices, Land Use and the Environment* (West Lafayette, IN: Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University)
- [14] United Nations Population Division DoEaSA 2011 *World Population Prospects: the 2010 Revision* (Washington, DC: United Nations) (available from: <http://esa.un.org/unpp/>, cited 2012)
- [15] USDA 2012 *USDA ERS International Macroeconomic Data Set* (Washington, DC: Service UER)
- [16] IEA 2010 *World Energy Outlook* (Paris: International Energy Agency)
- [17] Angel S, Parent J, Civco D, Blei A and Potere D 2010 A planet of cities: urban land cover estimates and projections for all countries, 2000–2050 *Working Paper* (Cambridge, MA: Lincoln Institute of Land Policy)
- [18] Fuglie K O 2010 Total factor productivity in the global agricultural economy: evidence from FAO data *The Shifting Patterns of Agricultural Production and Productivity Worldwide* ed J M Alston, B A Babcock and P G Pardey (Ames, IA: Iowa State University) pp 63–95
- [19] Ludena C E, Hertel T W, Preckel P V, Foster K and Nin A 2007 Productivity growth and convergence in crop, ruminant, and nonruminant production: measurement and forecasts *Agric. Econ.* **37** 1–17
- [20] Emvalomatis G, Stefanou S E and Lansink A O 2009 Dynamic decomposition of total factor productivity change in the EU food, beverages, and tobacco industry: the effect of R&D *A Resilient European Food Industry and Food Chain in a Challenging World* (Chania, Crete, 3–6 September)
- [21] Muhammad A, Seale J, Meade B and Regmi A 2011 International evidence on food consumption patterns: an update using 2005 international comparison program data *USDA ERS Technical Bulletin No. (TB-1929)* (Washington, DC: USDA ERS)
- [22] Plevin R J, Gibbs H K, Duffy J, Yui S and Yeh S 2011 *Agro-Ecological Zone Emission Factor Model* (<http://plevin.berkeley.edu/docs/Plevin-AEZ-EF-Model-Preliminary-Sep-2001.pdf>)

- [23] Schmitz C *et al* 2011 Trading more food: implications for land use, greenhouse gas emissions, and the food system *Glob. Environ. Change* **22** 189–209
- [24] Claussen M *et al* 2002 Earth system models of intermediate complexity: closing the gap in the spectrum of climate system models *Clim. Dyn.* **18** 579–86
- [25] Müller C, Bondeau A, Popp A, Waha K and Fader M 2010 Climate change impacts on agricultural yields *Background Note to the World Development Report 2010*
- [26] World Bank 2010 *World Development Report 2010: Development and Climate Change* (Washington, DC: World Bank)
- [27] Nelson G C *et al* 2009 *Climate Change: Impact on Agriculture and Costs of Adaptation* (Washington, DC: International Food Policy Research Institute)
- [28] Cline W R 2007 *Global Warming and Agriculture: Impact Estimates by Country* (Washington, DC: Center for Global Development)
- [29] Thirtle C, Lin L and Piesse J 2003 The impact of research-led agricultural productivity growth on poverty reduction in Africa, Asia and Latin America *World Dev.* **31** 1959–75
- [30] Alston J M, Chan-Kang C, Marra M C, Pardey P G and Wyatt T J 2000 *A Meta Analysis of Rates of Return to Agricultural R&D: Ex pede Herculem?* (Washington, DC: International Food Policy Research Institute)
- [31] Pardey P G 2006 *Agricultural Research: A Growing Global Divide?* (Washington, DC: International Food Policy Research Institute)
- [32] Saltelli A, Tarantola S, Campolongo F and Ratto M (ed) 2004 *Sensitivity Analysis in Practice: A Guide to Assessing Scientific Models* (Chichester: Wiley)
- [33] Bruinsma J (ed) 2009 *The Resource Outlook to 2050. Expert Meeting on How to Feed the World in 2050* (Rome: Food and Agriculture Organization of the United Nations)
- [34] Tilman D, Balzer C, Hill J and Befort B L 2011 Global food demand and the sustainable intensification of agriculture *Proc. Natl Acad. Sci.* **108** 20260–4
- [35] Hertel T W 2011 The global supply and demand for agricultural land in 2050: a perfect storm in the making? *Am. J. Agric. Econ.* **93** 259–75
- [36] West P C *et al* 2010 Trading carbon for food: global comparison of carbon stocks versus crop yields on agricultural land *Proc. Natl Acad. Sci.* **107** 19645–8
- [37] Enkvist P, Nauclér T and Rosander J 2007 A cost curve for greenhouse gas reduction *McKinsey Q.* **1** 34
- [38] Clarke L, Edmonds J, Krey V, Richels R, Rose S and Tavoni M 2009 International climate policy architectures: overview of the EMF 22 international scenarios *Energy Econ.* **31** S64–81
- [39] Barker T *et al* 2007 Technical summary *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed B Metz, O R Davidson, P R Bosch, R Dave and L A Meyer (Cambridge: Cambridge University Press) pp 25–94
- [40] Golub A A, Henderson B B, Hertel T W, Gerber P J, Rose S K and Sohngen B 2012 Global climate policy impacts on livestock, land use, livelihoods, and food security *Proc. Natl Acad. Sci.* at press (doi:10.1073/pnas.1108772109)
- [41] Ahmed S A, Hertel T W and Lubowski R 2008 Calibration of a land cover supply function using transition probabilities *GTAP Research Memorandum No.* 14
- [42] Gurgel A, Reilly J M and Paltsev S 2007 Potential land use implications of a global biofuels industry *J. Agric. Food Indust. Organ* **5** 9
- [43] Keeney R and Hertel T W 2005 GTAP-AGR: a framework for assessing the implications of multilateral changes in agricultural policies *GTAP Technical Paper Series No.* 24 (West Lafayette, IN: Purdue University)
- [44] USDA 2009 *Summary Report: 2007 National Resources Inventory* (Washington, DC and Ames, IA: Natural Resources Conservation Service and Center for Survey Statistics and Methodology, Iowa State University) (www.nrcs.usda.gov/technical/NRI/2007/_NRI_Summary.pdf)
- [45] Liu M and Tian H 2010 China's land cover and land use change from 1700 to 2005: estimations from high-resolution satellite data and historical archives *Glob. Biogeochem. Cycles* **24** 18
- [46] Weber C and Puissant A 2003 Urbanization pressure and modeling of urban growth: example of the Tunis Metropolitan Area *Remote Sens. Environ.* **86** 341–52