Climate change adaptation through agricultural R&D investments:

Implications for food security and the environment

Uris Lantz C. Baldos[1*], Thomas W. Hertel[1] and Keith O. Fuglie[2]

[1]Department of Agricultural Economics
Purdue University
West Lafayette, IN
[*]E-mail: ubaldos@purdue.edu

[2]Economic Research Service
U.S. Department of Agriculture
Washington, DC

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PRELIMINARY DRAFT AND RESULTS – DO NOT CITE

I. Overview

Land-based greenhouse gas (GHG) emissions account for a significant portion of global GHG emissions, and the majority of these emissions come from the conversion of natural lands to cropland and other commercial uses (Baumert, Herzog, & Pershing, 2005). The pace of such conversion hinges critically on crop yield growth. However, recent estimates suggest that yield growth – particularly for cereal staples – has been slowing down in key regions of the world (Alston, Beddow, & Pardey, 2009). Furthermore, as the recent IPCC-WGII report (2014) on climate impacts makes clear, climate change is likely to dampen future productivity growth, thereby accelerating land conversion, releasing additional GHG emissions into the atmosphere, and ultimately stimulating further climate change. Effective climate change adaptation is crucial in breaking this feedback loop and this can be achieved via sustained productivity growth from agricultural research and development (R&D).

The historic rise in global agricultural output and productivity during the 20th century has been made possible by aggressive agricultural R&D investments. With supply expansion exceeding that of demand, global food prices have reached their lowest levels in history benefiting millions who are food insecure. Productivity growth also helped dampen the environmental impacts from past expansion in global agricultural production. In the absence of historic yield improvements, as much as 1.1 to 1.7 billion hectares of natural lands would have been brought into agriculture resulting in substantial increases in CO_2 emissions from land conversion (Burney, Davis, & Lobell, 2010). This exceptional record of productivity growth has been knowledge driven, with public agricultural R&D leading the way. Given the long lags between R&D expenditures and productivity outcomes (Alston, Pardey, & Ruttan, 2008) and the threats posed by climate change on agricultural productivity (David B. Lobell, Schlenker, &

Costa-Roberts, 2011), investments made over the next two decades will likely prove critical in ensuring that global agriculture can meet the needs of the world by midcentury.

Because of its weight on future prospects for food and environmental security, evaluating the benefits and costs of climate adaptation through agricultural R&D spending is crucial in informing investment decisions particularly at a time wherein public research budgets are heavily constrained. Our research leverages on a comprehensive collection of historical estimates of national R&D expenditures and capital stocks, by region, worldwide, combined with differential research lags which govern how R&D expenditures are converted to capital stocks, and econometric estimates of the elasticity of total factor productivity growth (TFP) with respect to changes in R&D capital stocks in each region (Fuglie, 2014). We also take advantage of a newly published library of 36,000 climate impact results (Elliott et al. 2014; Rosenzweig et al. 2014; Villoria et al. 2014) in order to explore the full range of adverse yield impacts of climate change. By taking a sample of extreme combinations of global climate model and crop model results, we can identify the upper bounds of climate change productivity impacts.

With these information at hand, we then employ a partial equilibrium model of global agriculture which has been validated historically (Baldos & Hertel, 2013),to estimate the cost of effective adaptation to climate change extremes, and the GHG emissions from avoided cropland expansion. Previously, we demonstrated that such knowledge-based adaptation could indeed deliver cost-effective mitigation ($11-22/ton CO2e) (D. B Lobell, Baldos, & Hertel, 2013). However, our prior work did not incorporate explicit estimates of the R&D capital stock, nor did it allow for a conceptual model which links regional R&D expenditures to growths in capital stock and TFP. In this paper, we offer more refined estimates of these mitigation benefits and explore the costs of reducing vulnerability to future climate change across different trade regimes. We also examine the indirect contribution of these adaptation investments in strengthening future food security.

II. Model and methods

The SIMPLE model: The SIMPLE model (a Simplified International Model of agricultural Prices, Land use and the Environment) is designed to be as parsimonious as possible, focusing only on the key drivers and economic responses which govern long run food consumption and production. In the model, logistic per capita food demands are driven by exogenous per capita income growth and respond to endogenous changes in food prices. Food commodities covered in SIMPLE includes crops, livestock products and processed foods. Consumer responses to income growth and food prices evolve to reflect shifts in dietary preferences – moving away from crops towards livestock and processed foods.

Production systems in SIMPLE are modelled using a constant elasticity of supply (CES) production framework. Crops are produced by combining land and aggregate non-land inputs with the latter input representing all other factors of production – excluding land – which are used by the crops sector such as labor, machinery and working capital, pesticides and fertilizers, among other things. Once produced, crops are allocated towards direct food consumption, feed use in the livestock sectors, raw input use in the processed food industries, as well as feedstocks in the global biofuel sector. The capacity for input substitution between land and non-land inputs makes it possible to endogenously increase crop yields. However, in this paper we are interested in the evolution of the global farm system due to exogenous assumptions about productivity trends stemming from climate change and/or additional investments in agricultural R&D.

National and international markets facilitate interaction among economic agents and determine equilibrium food consumption, production and prices. The presence of tariff and non-tariff trade barriers, as well as other trade costs, diminishes the capacity of markets to respond to prevailing supply and demand conditions. Using a constant elasticity of transformation (CET) framework, we account for the implications of market barriers in SIMPLE by limiting market agents' capacity to access the global crop markets (Baldos & Hertel, 2015). With imperfect access to world markets, local and international crop prices do not move at the same pace. Of course, we also consider the case wherein crop markets are perfectly integrated and that there is only a single global crop market which determines the world crop price (Baldos & Hertel, 2013).

In the SIMPLE model, food security is reflected through adequate consumption of dietary energy (Baldos & Hertel, 2014). We use this framework to measure the food security gains from climate adaptation investments. Per capita food consumption is directly converted to caloric consumption equivalent. Furthermore, by characterizing the full distribution of caloric consumption within a region, using the lognormal distribution[1], and applying a minimum dietary energy requirement, it is possible to express malnutrition in terms of the average shortfall in caloric consumption amongst the undernourished population (FAO, 2012). Figure 1 summarizes how changes in per capita caloric consumption are translated into shifts in the distribution of caloric consumption specifically for Sub Saharan Africa in the years 2006 (solid black line) and 2050 (dashed blue line). The vertical dotted line within the 2006 distribution represents the minimum caloric requirement. The area to the left of this line is the fraction of the population which suffers from caloric consumption deficits. Going forward to 2050, rising per capita

[1] Early work by FAO (Neiken, 2003) found that the log-normal distribution has a better fit of household data on caloric consumption compared to other distributions. The log-normal is also widely used in the poverty literature to calculate the poverty headcount and poverty incidence (see Foster et al. (1984)) and similar indices can be constructed to measure the incidence and headcount of caloric undernutrition.

incomes lead to increased food and caloric consumption. Greater caloric intake shifts the distribution, resulting in a thinner tail to the left of the unchanging minimum caloric requirement. The malnutrition incidence in 2050 is the area bounded by the minimum dietary energy requirement and the new caloric distribution curve. Once calculated, the malnutrition index may then be combined with population data to derive the malnutrition headcount within a region.

We use the gridded emissions efficiency factors calculated by West et al. (2010) in order to measure the carbon stock loss when crop production expands. The authors calculate the emissions efficiencies by taking the crop yield per hectare of increased cropland, relative to the one-time carbon emissions associated with bringing that land into crop production. Thus, if the carbon stocks per hectare are the same in two regions, we have a larger penalty for cropland conversion in regions with lower yields. If this ratio is large in absolute value, then we say that the region has high emissions efficiency. The methods used to aggregate these grid-cell emission efficiencies are described in Hertel Ramankutty and Baldos (2014).

Climate change yield impacts: In this paper, we exploit a library of climate impact results based on the latest Global Gridded Crop Model (GGCM) inter-comparison project (Elliott et al., 2014; Rosenzweig et al., 2014). It provides a comprehensive evaluation of the productivity impacts imposed by climate change on global agriculture. These yield impacts vary across crop, space and time, and also consider the absence/presence of CO_2 fertilization as well as irrigation. The results of the GGCM inter-comparison project are available to the public and can be freely accessed using the AgMIP tool developed by Villoria, Elliott, Choi, & Zhao (2014) (https://mygeohub.org/tools/agmip).

Following Baldos and Hertel (2015), climate change productivity shocks which we adapt in this paper are constructed using global yield projections for the 21st century for 4 rain-fed crops (maize, rice, wheat and soybean) based on the results from the pDDSAT and the LPJmL crop models. These shocks are calculated given future climate generated using five GCMs[2] under the RCP8.5 scenario which assumes that GHG emissions and atmospheric concentrations are expected to rise sharply in the future. Grid-cell yield outcomes are then aggregated to regional levels in the SIMPLE model using gridded crop production data from Monfreda et al. (2008). We then aggregate across all four crops using crop production values from FAOSTAT (2014) to derive the final productivity shocks for each region. Figure 2 summarizes the crop yield impacts from climate change which are used in the future projections. Note that we omitted the CO_2 fertilization effects so that the expected crop yield reductions from climate change are generally steeper.

Productivity gains from R&D investments: We rely heavily on the historical R&D spending and capital stocks data provided by Fuglie (2014) in estimating the cost of climate adaptation. Data on 5-year agricultural R&D expenditures – which extends up to the 1930s – is converted to agricultural R&D capital stocks using a trapezoidal lag structure. These R&D lag structure captures the temporal process of technological innovation starting from initial research efforts towards commercial development and adoption of new technologies in the production system (Alston, James, Andersen, & Pardey, 2010). The length of the lag-structure is region-specific with longer lags for developed than in developing regions (50-year and 35-year lags, respectively). Given this, the productivity impacts from increased R&D spending are realized faster in developing regions. Once constructed, the stream of R&D capital stocks are converted

[2] These consists of HADGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M, NorESM1-M. For convenience, these models are mentioned in the paper as HADGEM,IPSL,MIROC,GFDL,NORESM, respectively

to growth rates in agricultural total factor productivity via the R&D TFP elasticities. We then use the estimates in the literature as a guide and calibrate the R&D TFP elasticities separately for developed (at around 0.25) and developing regions (between 0.16 and 0.28). Note that we only focus on the productivity growth due to increased spending in national public R&D and exclude the impact of private R&D spending.

Experimental Design: The benefits and costs of climate change adaptation are computed from the differences between future scenarios with and without climate change. In the absence of climate change, the global farm and food system is projected from 2006 to 2050 using key growth rates in Table 1. In the coming decades, it is expected that population and per capita incomes will dictate future food demand. The population and income growth rates are based on the Shared Socio-economic Pathways (SSP) Database (2013). These SSPs have been specifically designed for climate change impact assessment by providing alternative trends in socio-economic development when climate change impacts are ignored (Kriegler et al., 2012; O'Neill et al., 2014). In this study, SSP 2 is used, which assumes that future socio-economic and technological development permits successful implementation of climate change adaptation and mitigation strategies (Kriegler et al. 2012). The recent assessments of the potential impacts of climate change on crop yields worldwide which are used in this study are also based on SSP 2 projections (Elliott et al. 2014; Rosenzweig et al. 2014). In addition to population and income, future food demand will also be affected by crop feedstock demand for first and second generation biofuel production. Projections of global biofuel consumption is based on the "Current policies" scenario published in the World Energy Outlook (IEA, 2008, 2012). These forecasts are based on the results of a detailed world energy model given exogenous growths in GDP and population as well as assumptions on future energy prices and technology. With the

“Current policies” scenario, all energy policies for the power and transportation sectors enacted as of mid-2012 are taken into account. We also consider productivity improvements in the livestock and processed food sectors. Regional TFP growth rates for the livestock sectors are based on the projections from Ludena et al. (2007). Lacking detailed TFP projections for the processed food sector, historical rates from Griffith et al. (2004) is used, assuming that these rates apply in the future and across all regions.

Effective climate change adaptation can be achieved via sustained productivity growth driven by agricultural research and development (R&D). However, such adaptation strategies require increased investments in agricultural R&D. To calculate the cost of adaptation, we first establish the future baseline TFP growth in the crop sector by assuming that historical R&D spending rates will persist in the absence of climate change. Of course, with climate change agricultural productivity is expected to decline and to offset the adverse effects increases in R&D spending is required. The cost of climate change adaptation is then derived from the difference between the future baseline spending and the increased R&D spending given climate change. Of course, in regions wherein climate change impacts are positive additional spending is not required. Given the lagged effects of R&D spending on agricultural total factor productivity growth, we also explore the implications of early (2016-2050) and late (2036-2050) investments in climate change adaptation.

III. Preliminary Results

Adverse temperature and precipitation from climate change dampens agricultural productivity. To meet increased food demand in the future, farmers offset these unfavorable productivity shocks by using more inputs; thus expanding cropland use resulting in loss of natural carbon stocks. Figure 3 shows global cropland use expansion and carbon stock loss associated with climate change. We summarize the results given changes in climate generated from five GCMs and expected productivity impacts given the pDDSAT and LPJmL crop models. Each range is constructed from the deviations in global cropland use expansion and carbon stock loss in the presence of climate change relative to the 2050 baseline without climate change. We also contrast the results when crop markets are perfectly integrated (left panel) and when market barriers persist in the future (right panel).We immediately observe that the upper and lower bounds across GCMs are based on the results from the LPJmL and pDDSAT models, respectively. Of course, this is not surprising given the sharp reduction in crop yields under the former crop model (see Figure 2). Among GCMs, climate change impacts under the MIROC GCM result in significant levels of global cropland expansion and reduction in natural carbon stocks. In particular, the range of global cropland expansion and carbon stock loss under this GCM is around 134-94 M hectares and 1.5-1.1 B CO_2 equivalent, respectively. Market barriers have significant implications for environmental security in the presence of climate change impacts, as the range of cropland expansion and carbon stocks loss are substantially smaller when markets are less integrated. For example, under the MIROC GCM the ranges of global cropland expansion and carbon stock loss fall to around 95-67 M hectares and to 1.0-0.7 B CO_2 equivalent, respectively

Climate change will alter the comparative advantage of crop production worldwide. If global markets can be freely accessed then farmers in regions which are least affected by adverse climate change shocks will respond by expanding crop production and increasing input. Looking at our regional yield shocks in Figure 2, we see that crop production in South Asia and North Africa are largely at risk for large productivity losses due to climate change; hence, crop grown in these regions will likely be produced elsewhere. Introduction of trade barriers (market segmentation) hinders access to the world markets; limiting the capacity to increase crop production in unaffected/less affected regions. Under this scenario, the regional impacts of climate change will shape the required expansion in cropland use and subsequent carbon stock loss.

With the results in Figure 3 at hand, we can now examine the benefits and costs associated with climate adaptation from increased national R&D investments in agriculture. Table 2 show the gains in environmental and food security associated with an increase in average R&D spending by around 1M USD / year[3]. We focus on the required investments needed to offset adverse climate change impacts generated under the MIROC GCM which gives us the upper bounds of cropland expansion and carbon stock losses. Aside from the implications of trade barriers, we also explore how the timing of R&D investments affects the benefits from climate change adaptation. Looking at the tables, we see that the associated benefits from increased R&D investments are notably higher when markets are fully integrated. For example, an increase in average R&D spending by around 1M USD / year results in avoided cropland expansion of around 2.0-1.8 thousand hectares when markets are fully integrated or around 1.4-1.3 thousand hectares when trade barriers persists. The amount of avoided carbon stock loss from this investment is between 23.9-20.4 and 15.0-13.3 thousands MT CO_2 equivalent under the integrated and segmented markets, respectively. Note that the range of implied carbon cost from climate change adaptation which we calculated is quite larger than our previous estimate ($11-22/MT CO2e). Indeed, we computed that the implied carbon costs from increased R&D

[3] We first calculate the required increase in R&D spending in order to offset the adverse productivity impacts of climate change. We then take the net present value of total R&D cost, using 3% as the discount rate,and calculate the average annual increase in R&D which we used to calculate the per unit costs of the benefits from R&D which we used to calculate the gains in increased R&D investments.

investments ranges from 42-49 and 67-75 USD / MT CO2 equivalent under the integrated and segmented markets, respectively. Of course, this is not surprising since our previous work ignored the temporal transformation of R&D spending to R&D capital stocks. Furthermore, we assumed that elasticity of agricultural TFP growth are uniform across regions and are close to the values estimated for developed regions (around 0.30). Nevertheless, the carbon costs which we estimated are still within the observed carbon prices (World Bank, 2015) implying that climate change adaptation through increased agricultural R&D spending could still be cost effective. Furthermore, we also see that agricultural R&D investments can lead to improvements in food security lifting thousands out of extreme hunger.

Delayed action will results in significantly lower benefits from climate change adaptation. Specifically, the gains in additional R&D investments are significantly lower if we wait until 2036 before investing in climate adaptation - around 45% lower than the gains if we invest starting in 2016. The costs per avoided carbon loss are also higher, with estimates at around 74-92 and 118-141 USD / yr / MT CO_2 equivalent under the integrated and segmented markets. These results highlight that delayed adaption to climate change will be more costly.

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Figure 1. Changes in caloric distribution in Sub Saharan Africa: 2006 vs 2050

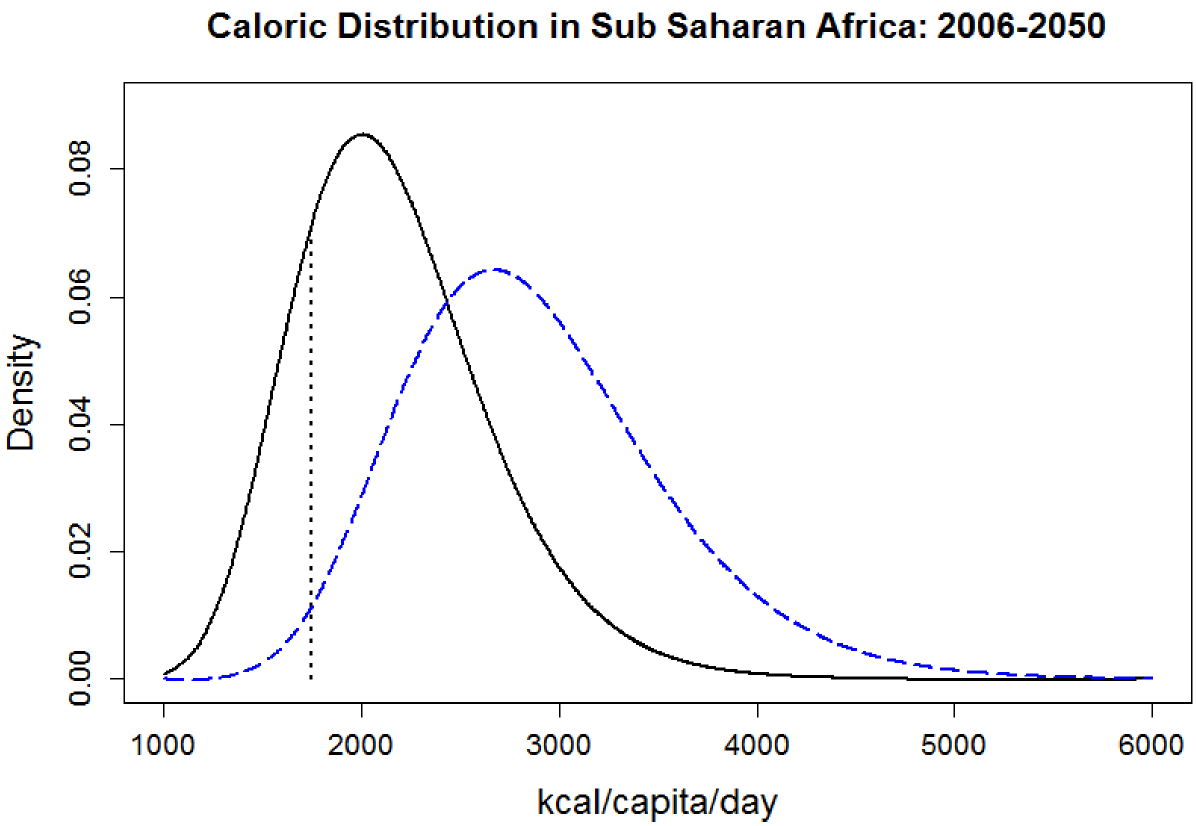
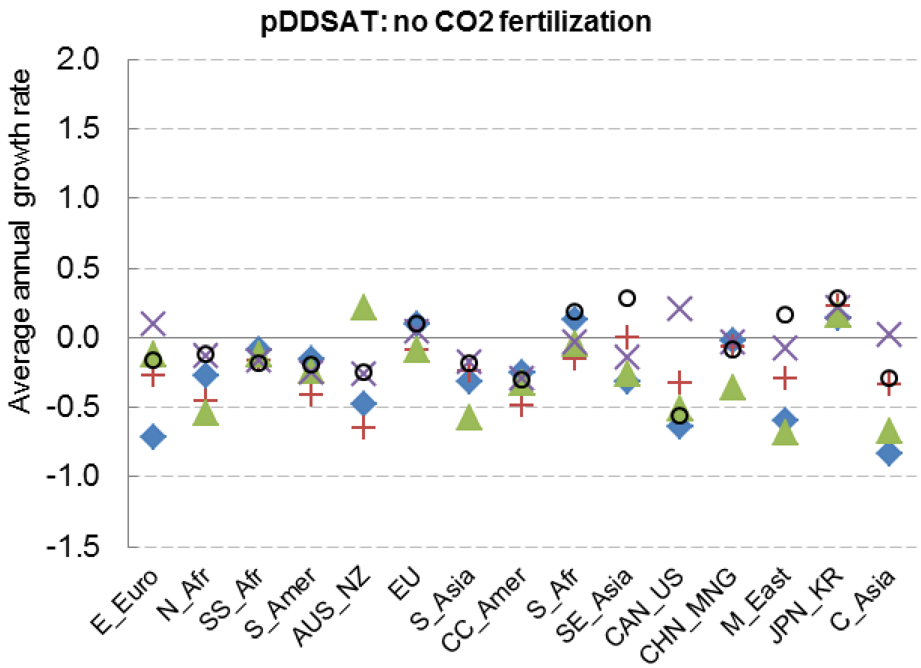


Figure 2. Changes in crop yield due to climate change across global circulation and crop models: 2006 vs 2050



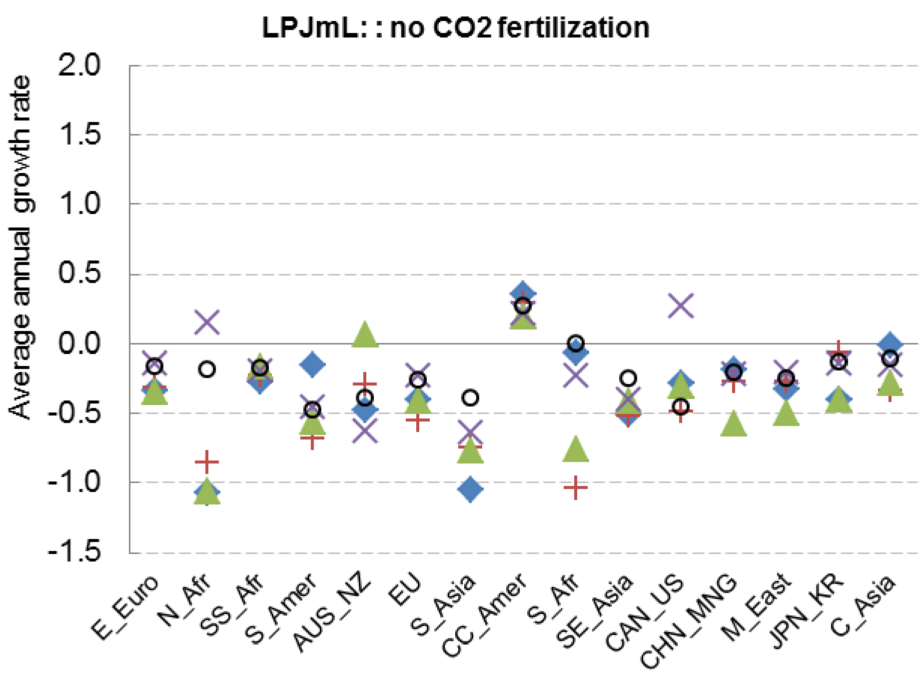


Figure 3. Global cropland expansion and carbon stock loss under climate change given global circulation and crop models: 2006 to 2050

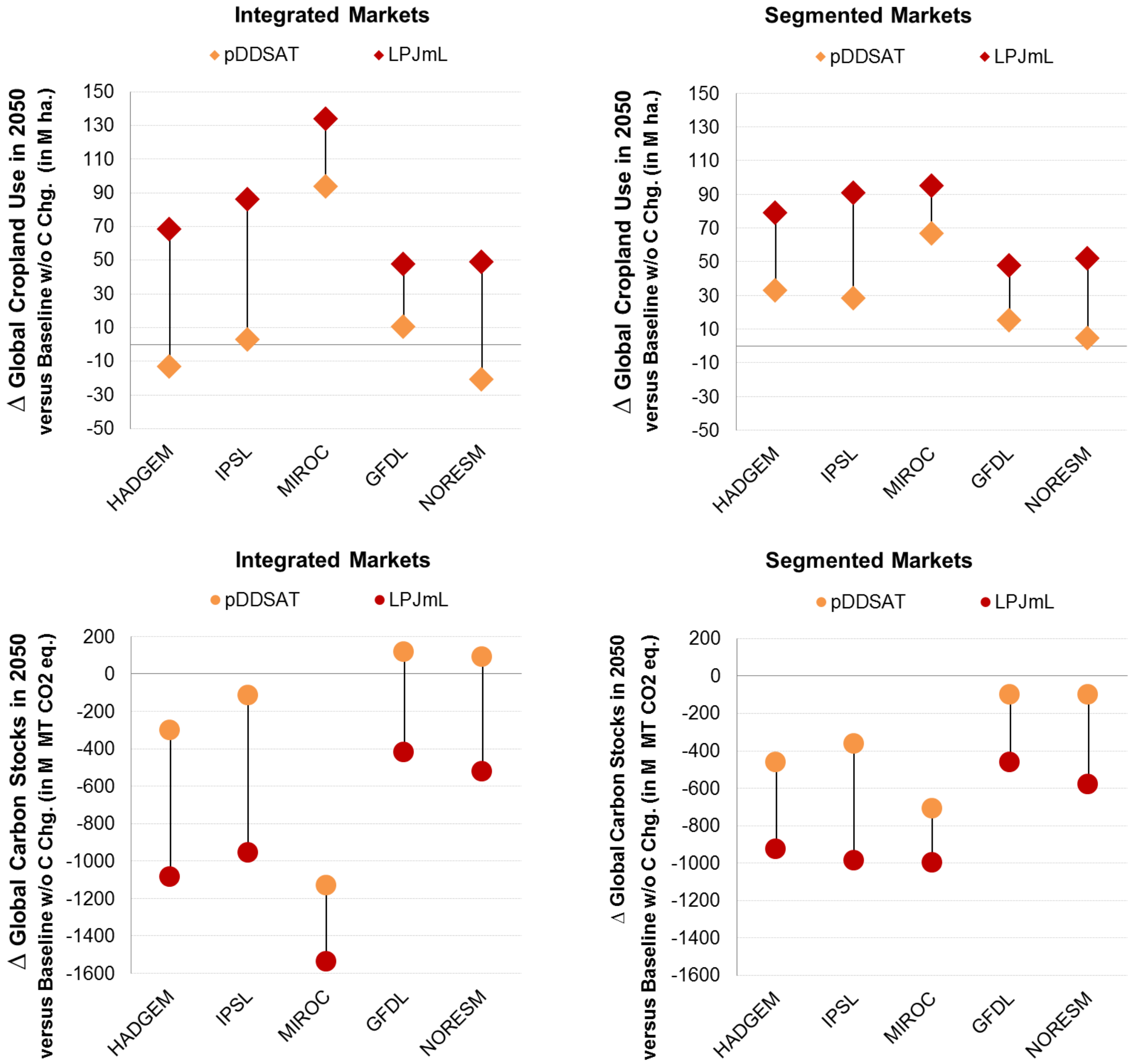


Table 1. Key growth rates for future simulation: 2006 to 2050

Regions	Population	Per Capita Income	Biofuel	Total Factor Productivity	
				Livestock	Processed Food
Eastern Europe	-0.13	3.20		1.04	
North Africa	1.05	3.07		-0.30	
Sub Saharan Africa	2.05	3.49		0.43	
South America	0.73	2.47		2.64	
Australia/New Zealand	1.23	1.32		0.42	
European Union+	0.27	1.27		0.42	
South Asia	1.07	4.17		1.71	
Central America	0.83	2.02		2.64	
Southern Africa	0.73	2.62		0.43	
Southeast Asia	0.80	3.69		2.38	
Canada/US	0.74	1.17		0.42	
China/Mongolia	0.07	5.26		2.38	
Middle East	1.43	2.06		-0.30	
Japan/Korea	-0.17	1.56		0.42	
Central Asia	0.67	4.68		1.04	
World	0.83	2.41	5.80	2.15	0.89

Table 2. Climate adaptation benefits from increased R&D spending in agriculture: 2006 to 2050

Benefits from agricultural R&D investments (1 M USD / yr)		
Avoided Cropland Expansion (in ha.)	pDDSAT	LPJmL
Integrated Markets		
2016-2050	1974	1772
2031-2050	1114	949
Segmented Markets		
2016-2050	1410	1260
2031-2050	795	675
Avoided Loss in Carbon Stock (in MT CO2 eq.)	pDDSAT	LPJmL
Integrated Markets		
2016-2050	23870	20382
2031-2050	13464	10915
Segmented Markets		
2016-2050	14995	13268
2031-2050	8458	7105
Malnutrition Alleviation (in persons)	pDDSAT	LPJmL
Integrated Markets		
2016-2050	1902	1904
2031-2050	1073	1020
Segmented Markets		
2016-2050	2418	2229
2031-2050	1364	1193